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ECONOMIC GEOLOGY

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THE INFLUENCE OF PERMEABILITY ON ORE DISTRIBUTION IN LIMESTONE AND DOLOMITE.[1]

ERNEST L. OHLE.

PART I.

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ABSTRACT.

The general knowledge of rock permeability has been reviewed in the light of fundamental work done since Rove's pioneer study, and an attempt has been made to evaluate the influence of permeability on ore distribution in limestone and dolomite. Over 1,000 permeability determinations were made, principally on rocks from the East Tennessee Zinc District. A permeameter is described which was especially designed to measure permeabilities in the range 10^{-2} to 10^{-7} millidarcies, using either liquid or gas as the test fluid.

[1] This is paper No. 126 published under the auspices of the Committee on Experimental Geology and the Division of Geological Sciences at Harvard University. It was presented before the Washington meeting of the Geological Society of America in November, 1950.

The potential sources of error in using gas-flow results to predict liquid flow through rocks are discussed with particular note being given to Klinkenberg's discovery that only at infinite mean gas pressure will "gas permeability" approximate "liquid permeability."

In the East Tennessee Zinc District the permeability values fall into three main groups corresponding to the three principal rock types: "original" dolomites, limestone, and "recrystalline," the latter an alteration product of the limestone near mineralization. Alteration of certain beds by the mineralizing solutions prior to sulphide introduction increased their permeability many fold; disseminated replacement ore is virtually restricted to these beds. Calculations from test results show that, under reasonable geologic conditions, large volumes of aqueous solutions can pass through rocks of the "recrystalline" type. In all probability a sufficient volume of dilute ore solution could pass through these rocks to account for all the ore deposits found in them.

INTRODUCTION.

THE ability of ore solutions to single out certain layers in a series of limestone beds as favored loci for ore deposition has long been noted but never satisfactorily explained. In many mining districts the difference between "favorable" and "unfavorable" formation is too subtle to be perceived with the naked eye or, indeed, even with the aid of a microscope. Yet, to the ore solution seeking a place to deposit its metallic load, the difference must be striking for the "elected" strata are sought out and followed through all the contortions of intense folding, and dislocated and isolated blocks of the favored beds are sought out and impregnated with ore minerals.

In recent years considerable attention has been given to the problem of determining just what properties of certain formations or of certain beds with those formations make them particularly attractive for sulphide mineral deposition. To this end, Rove [2] made a study of the permeability, crushing strength, impact strength, and grindability of the favored ore horizons and the immediately overlying and underlying less favorable beds in eight mining districts. This is the most comprehensive treatment of the problem yet attempted. Of the physical properties studied, only permeability and crushing strength gave a positive correlation with ore distribution and hence seemed worthy of further study.

In concluding his report, Rove suggested that the next step in experimentation should be a more detailed study based on a large number of specimens from a single area.[3] The present study follows up this suggestion. As part of a broad consideration of the relation between permeability and ore distribution, 69 samples of different favorable and unfavorable beds in the East Tennessee Zinc District were collected and their permeability determined. An effort has been made to evaluate the influence of rock permeability on the flow pattern of the ore solution and also to determine the effect on rock permeability of the alteration caused by these solutions.

Difference in permeability has been credited with having influenced the

[2] Rove, Olaf, Some physical characteristics of certain favorable and unfavorable ore horizons: ECON. GEOL., vol. 42, pp. 57–77, 161–193, 1947.

[3] Idem, p. 192.

selective replacement of specific beds in many districts. In many cases there is no more evidence on which to base this conclusion than the mere presence or absence of ore in the several layers. In others, beds are said to be more permeable because they *look* more permeable. Neither of these lines of logic is valid. Other rock properties—such as great chemical reactibility—may be characteristic of only moderately permeable beds and may offset the difference in permeability. This study has revealed that some rocks which look very permeable permit less flow than other rocks which appear "tight." Actual flow measurements are necessary and reports of such measurements are extremely scarce in the literature of mining geology. A permeameter of simple design is described in this report. Once the apparatus is set up, the tests are easy and rapid. It is hoped that the future will see more precise usage of the terms "permeable" and "impermeable" and more specific data on which to base judgements of rock permeability relations.

It is a pleasure to acknowledge the contributions made by others during the course of this investigation. Particular thanks are due Dr. L. C. Graton, who originally suggested the project and outlined its objectives, and Dr. Francis Birch, who guided the experimental work and proposed most of the useful features of the permeameter. Additional thanks are due to them and to Dr. H. E. McKinstry and Dr. Russell Gibson for critically reading the manuscript.

Several companies and their officers made this study possible by their cooperation. Mr. Howard I. Young, President of the American Zinc, Lead, and Smelting Company, and Mr. E. B. Jennings, General Superintendent of the Universal Exploration Company, kindly granted access to the mine workings of their respective companies and permission to take samples of the ore formation. Mr. R. L. McCann, General Manager of Mines of the New Jersey Zinc Company, arranged for the collection of samples from that company's operations at Gilman, Colorado, Hanover, New Mexico, and Franklin, New Jersey.

The microphotographs were taken by Mr. Kenneth Holke, Research Assistant at Washington University, and the photographs of the hand specimens were made by Mr. Vincent AuBuchon, Safety Engineer of the St. Joseph Lead Company. Mr. Arnold Brokaw of the United States Geological Survey assisted in collecting the samples at Jarnagin Mine and made available diamond drill cores which he had previously collected. Mr. L. A. Rice, Chemist of the St. Joseph Lead Company, made the analyses of the limestones and dolomites. Mr. Harold Ames of Harvard University contributed valuable suggestions in the design and construction of the permeameter.

THE GENERAL NATURE OF POROSITY AND PERMEABILITY.

"The porosity of a rock is its property of containing interstices. It is expressed quantitatively as the percentage of the total volume of the rock that is occupied by interstices or that is not occupied by solid rock material." [4]

[4] Meinzer, O. E., et al., Hydrology, Physics of the Earth Series, vol. 9, p. 387, McGraw-Hill Book Co., New York, 1942.

"The permeability of a porous medium may be defined as the volume of a fluid of unit viscosity passing through a unit cross section of the material one centimeter thick under unit pressure gradient in unit time." [5]

These two related rock properties at times have been confused but the difference between them has been discussed so thoroughly in recent years that no extensive elaboration seems necessary.[6] The capacity to transmit fluids, i.e., permeability, obviously involves use of the rock pores. The relationship is decidedly not linear, however, for some rocks with high porosities, such as shale and scoria, have lower permeabilities than other rocks with much lower porosity.

A number of special terms involving particular dimensions of both porosity and permeability are found in the literature. Thus we find such terms as "available porosity," "initial permeability," "effective permeability," "effective directional porosity," and "critical permeability" in common use. These terms refer to the porosity or permeability extant at a given time or in a given direction through the rock. The last two are particularly pertinent in discussions of permeability as related to ore disposition.

"Effective directional porosity" may be defined as that portion of a rock's total porosity which is used in transmitting fluids in a given direction. Because of greater size or a greater abundance of throughgoing pore spaces in one direction than in another, this property may vary widely in different directions.

Graton [7] has defined "critical permeability" as "that permeability which is in effect at the specific time when the mineral in question is being precipitated." In the case of a succession of minerals being deposited in the interstices of a sandstone or conglomerate, the critical permeability of each mineral would thus be lower than that of its predecessor, unless solution activity or fracturing interrupted the sequence. As Fraser has shown,[8] the reduction in permeability due to cementation (of an aggregate of spheres) is much greater than would be expected from the reduction of porosity.

There is a fundamental difference between ores in sandstone or conglomerate and replacement deposits in limestone or dolomite. In the case of the former, deposition primarily is a matter of void filling with the porosity and permeability being much reduced in the process; in the case of the latter, reaction with and replacement of the carbonate are the significant processes and the filling of intergranular open spaces often is a very minor factor. In these, the porosity and permeability sometimes are increased by excess solution over deposition.[9]

[5] Rove, Olaf, op. cit., p. 61.

[6] For an excellent account see the paper by Graton, L. C., and Fraser, H. J., Systematic packing of spheres with particular relation to porosity and permeability: Jour. Geology, vol. 43, no. 8, pt. 1, pp. 785–909, 1935.

[7] Graton, L. C., Hydrothermal origin of the Rand gold deposits, part 1: Econ. Geol., vol. 25, supplement to no. 3, p. 63, 1930.

[8] Fraser, H. J., An experimental study of permeability with respect to ore deposition, unpublished thesis, Harvard University, p. 58, 1930.

[9] There are, of course, many ore bodies in carbonate rocks consisting of fissure veins and breccia filling. In these, ore deposition markedly decreases the porosity and permeability. The text refers specifically to deposits resulting primarily from replacement of carbonate rocks by the ore minerals.

If the ore minerals are deposited as a dissemination in which the individual sulphide particles are grain-for-grain replacements of the carbonate grains, a common situation well exemplified in some ore bodies in the Southeast Missouri Lead District, there need be no change at all in the permeability as a result of ore formation. If the replacing sulphide grains are smaller than the carbonate grains which they attack, the permeability may be reduced. When the individual sulphide grains form at the expense of several or many carbonate grains and the ore is much coarser than the original rock, a change in permeability is almost certain and, in this case, the permeability may be decreased but probably in most cases is increased by ore deposition.

In the series of permeability measurements listed in Table 1 in which the average grain size of the rocks progressively increases, the permeability also increases. This series involves replacement of fine limestone by coarser dolomite but it seems probable that the replacement of a fine grained carbonate rock by coarser sulphides would also result in increased permeability—the opposite effect from that resulting from deposition in the coarser clastic rock types. The data in Table 1 give quantitative support to the oft-repeated phrase that the coarser limestones or dolomites are favorable because they are "probably more permeable." [10]

Throughout this paper, the term "permeability" is used to mean intergranular permeability unless otherwise specified. In many cases, what has been measured is not the same as the primary permeability of the rock because specimens were selected representing all stages and types of alteration as well as the original conditions. Neither is it the same as the permeability that would obtain in a large block of rock including fractures, shear zones, and other avenues of grosser transport. Rather, we are here dealing with the capacity of the unfractured rocks to permit flow outward from the major channelways through the intergranular spaces of the solid rock itself, in whatever state or condition the rock may have presented at the time of flow of the ore fluids.

A number of efforts have been made to produce equations by which permeability could be calculated from porosity or mechanical composition data. Notable among these are the formulae of Hazen,[11] Slichter,[12] Fair and Hatch.[13] None of these is more than roughly quantitative except under ideal circumstances and they are not in general use.

Because the greatest volumes of fluid in intergranular motion (chiefly ground water and petroleum) move through sandstone or unconsolidated clastic sediments and because of the economic significance of these fluids, practically all of the experimental work on permeability has used sandstones or clusters of spheres as the porous medium. Relatively little work has been done on chemically precipitated rocks. The use of sandstones has the advan-

[10] The relation between coarseness of grain and permeability is also indicated by tests of specimens of Barriefield, Ontario, granite, Quincy, Massachusetts, granite, and Hudson, New York, diabase which indicated permeabilities of 5.1×10^{-5}, 4.6×10^{-3}, and 8.4×10^{-4}, respectively. The granites are coarse while the diabase is fine grained.

[11] Hazen, A., Some physical properties of sands and gravels with special reference to their use in filtration: Mass. State Board of Health, 24th Ann. Rept. (1892–93), p. 554.

[12] Slichter, C. S., U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 322, 1899.

[13] Fair, G. M., and Hatch, L. P., Fundamental factors governing the streamline flow of water through sand: Am. Water Works Assoc. Jour., vol. 25, no. 11, pp. 1551–65, 1933.

TABLE 1.

VARIATION IN PERMEABILITY OF EAST TENNESSEE ROCKS WITH INCREASED AVERAGE GRAIN SIZE

Spec. no.	% Calcite	% Dolomite	% Total Carbonate		Insol.	Fe, Al, Mn	Perm. (millidar.)
			Calcite	Dolomite			
13	92.14	4.11	99.0	1.0	3.2	.4	4×10^{-6}
43-2	89.30	2.74	97.0	3.0	6.4	.5	6.5×10^{-6}
47-2	92.79	3.20	96.6	3.4	1.8	.5	3.2×10^{-6}
90	91.49	4.57	95.2	4.8	3.3	.3	6×10^{-7}
34	79.71	10.97	87.6	12.4	10.7	.8	4.8×10^{-4}
92	84.76	12.34	87.2	12.8	3.1	.3	7.2×10^{-5}
15-1	77.26	15.08	83.6	16.4	6.7	.7	3.3×10^{-4}
14-1	63.76	26.61	70.5	29.5	8.4	.9	4.3×10^{-5}
44-1	15.25	61.24	20.0	80.0	21.3	1.6	9×10^{-5}
45-1	11.48	58.04	16.5	83.5	27.4	2.7	4×10^{-4}
12-2	7.85	53.93	12.7	87.3	6.4	1.2	2×10^{-3}
93	11.21	84.08	11.8	88.2	2.7	1.2	10×10^{-4}
48-2	10.5	81.8	11.3	88.7	5.0	1.6	1.4×10^{-3}
33-1	6.24	79.52	7.3	92.7	11.8	1.2	3.9×10^{-3}

The specimens are approximately in the order of increasing average grain size. The average grain size varies from .015 mm. in No. 13 to 1.25 mm. in No. 33-1.

A darcy is defined as the permeability of a substance which permits the flow of one cubic centimeter per second per square centimeter of sectional area, per centimeter of thickness, under a pressure gradient of one atmosphere, when the fluid viscosity is one centipoise.

Analyses by L. A. Rice.

tage that the grains are somewhat uniform in shape and size, the shapes of the openings are relatively simple, and a mathematical relationship between porosity and permeability (as in the Slichter and King Formulae) can be at least approximated.

In the case of chemically precipitated sediments, the grains are polyhedral and irregular and they fit closely together or are interlocking. Thus there are more variables in the relationship between grain size and shape and pore size and shape, and simple mathematical formulae can not be applied. Also, the interlocking character of the grains and the fact that they are acid soluble make it more difficult to compile mechanical composition data.

Ryder [14] has investigated the relations of permeability to pore size, pore shape, and the nature of the pore walls. He found a definite relationship between permeability and pore size and shape according to the equation:

$$K = Cd^n,$$

in which K = permeability,
C = factor depending on pore density and shape,
d = average dimension of the pores.

It was found that the exponent of "d" depended on the shape of the pores, particularly their degree of curvature and direction of transverse curvature. The unit of length of "d" is apparently of the order of one micron and "n"

[14] Ryder, H. M., Permeability, absolute, effective, and measured: World Oil, vol. 128, pp. 173–177, 1948.

varies between approximately 0.5 and 4. "*d*" is the reciprocal of "*b*" in Equation 2 on page 674. For pores of ideal shape the "*n*" values are as follows:

Capillary tube of circular cross section	4.
Parallel walls	3.
Openings between sharp, angular grains	1.6
Openings between spherical grains	0.5

By determining the slope of the curve, K vs. d, for a given sandstone, Ryder arrives at the value of "*n*" and, from this value, he deduces something about the shape of the pores. Different sand formations have characteristic pore shapes. Practical use is made of this fact in planning water flooding campaigns for secondary oil recovery.

No reports have been found of similar tests being made on carbonate rocks but it does not seem unlikely that the same kind of variation may exist in limestone and dolomite formations. The continuity and shape of the channelways along with their size and abundance are determining factors in rock permeability. Bain [15] has described a method of measuring the coefficient of grain irregularity in a rock and the width of the intergranular openings. Table 1 indicates the close relationship between permeability and average grain size in the recrystallized limestone of the East Tennessee Zinc District and Figure 1 shows the nature of the grain contacts in the bed when altered. Coarsening of the grain greatly reduces the number of pores but the newly created interstices are larger and in addition they are much straighter and smoother, and longer from offset to offset. The routes presented to transmitted fluids by such recrystallized rock are far less devious than those available in the original fine grained limestone. Since the coarse grains tend to have plane boundaries, the flow is essentially between parallel walls and "*n*" should be of the order of 3.0. Fraser [16] has reproduced a figure from E. Graustein showing the calculated flow through a circle with diameter of 1 and other shapes of the same cross-sectional area. For both laminar and turbulent flow, the flow between parallel plates (i.e., a rectangle) gives the greatest flow per area. For turbulent flow, the order of increasing flow is: equilateral triangle, 60° rhombus, square, ellipse, circle, and parallel plates. No order is given for laminar flow.

CALCULATION OF PERMEABILITY FROM TEST RESULTS.

When a liquid is the fluid passed through a specimen, the equation used to calculate the permeability is:

$$K = \frac{\mu Q L}{A(P_1 - P_2)}, \tag{1}$$

in which K = permeability (in darcys),

μ = viscosity of the liquid (in centipoises),

Q = volume rate of flow (in cubic centimeters per second),

L = length of column (in centimeters),

A = cross-sectional area (in square centimeters),

$P_1 - P_2$ = pressure difference through the specimen (in atmospheres).

[15] Bain, G. W., Measuring grain boundaries in certain crystalline rocks: Jour. Geology, vol. 49, pp. 199–206, 1941.

[16] Fraser, H. J., op. cit., pp. 114–115.

The equation which applies for the flow of a gas is:

$$K = \frac{Q_m \mu L}{A(P_1 - P_2)} \times 1 + \frac{4C}{P_m R} \quad \text{or} \quad \frac{Q_m \mu L}{A(P_1 - P_2)} \times 1 + \frac{b}{P_m}, \tag{2}$$

in which P_m = mean pressure,

Q_m = volume flux at the mean pressure,

C = ratio between the mean free path and the reciprocal of the mean pressure,

μ = viscosity of the gas at the mean pressure,

R = an average capillary radius so far as the slip correction is concerned,

$$b = \frac{4C}{R}.$$

The derivation of the permeability equations and the history of their development through 1937 is summarized by Clough [17] and by Muskat.[18] The fundamental equation is that of d'Arcy wherein the flow is shown to be proportional to the "head":

$$Q = \frac{KA(P_1 - P_2)}{L}, \tag{3}$$

with Q = volume rate of flow,

K = permeability factor,

A = cross-sectional area,

$P_1 - P_2$ = pressure differential,

L = length of the column.

This equation is widely used, being applied without appreciable error to flow through unconsolidated and consolidated sands and other highly permeable media. It has been substantiated by thousands of observations involving many different liquids. It is applicable so long as the flow is laminar rather than turbulent; turbulence involves lost energy due to increased friction and the relationship of Equation 3 no longer applies. Darcy's Law is so generally accepted that so long as the flow remains proportional to the pressure difference, it is assumed that the flow is laminar.[19]

Until 1941 it was generally believed that so long as the flow was proportional to the "head," the permeability of a porous medium was a fundamental property of the substance, independent of the liquid or gas used in the determination. Thus, in order to find out how much of a given fluid would pass through a porous medium, it was thought to be necessary simply to measure the flow of some convenient fluid and then calculate the flow of the given fluid by applying a viscosity correction. Generally, the volume of water or petro-

[17] Clough, K. H., Study of permeability measurements and their application to the oil industry: Oil Weekly, vol. 83, no. 4, pp. 27–34, 1936.

[18] Muskat, Morris, The flow of homogeneous fluids through porous media, McGraw-Hill Book Co., New York, 1937. See also Muskat, Morris, Physical principles of oil production, McGraw-Hill Book Co., New York, 1949.

[19] Muskat, Morris, op. cit., pp. 56–59, discusses the validity of Darcy's Law and the transition from laminar to turbulent flow.

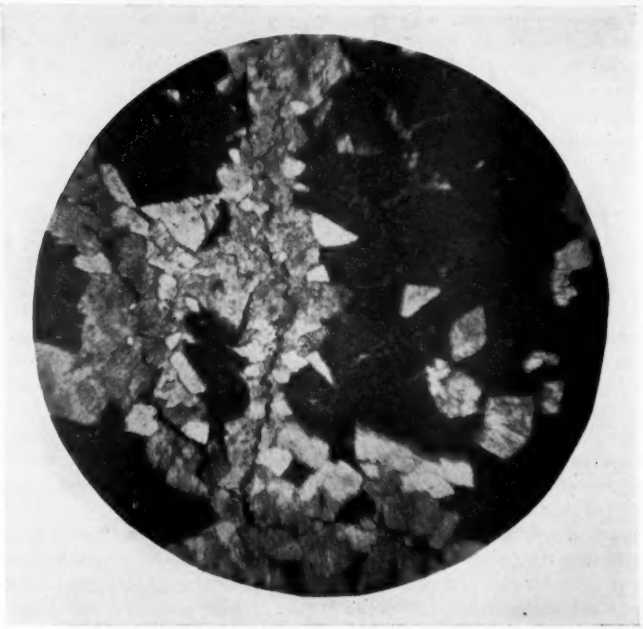


FIG. 1. Coarse "recrystalline" dolomite replacing fine grained U-bed limestone along stylolites and in scattered areas. Specimen ET-14, Jarnagin Mine, East Tennessee Zinc District, × 20.

leum that a rock would pass was what was sought. Since the measurement technique using a gas is much simpler and eliminates certain sources of error, it was general practice to use air in the tests following the procedure outlined by the American Petroleum Institute.[20]

In 1941, Klinkenberg showed that this method was in error so far as gas determinations were concerned unless the experimental procedure was modified.[21] He found that, while permeability is a fundamental rock property so far as liquid transmission is concerned, the results in gas experiments performed by the then accepted method would always be too high, and further, that different results would obtain when different gases are used. Thus, obviously, the general practice of using gas permeability determinations as measures of liquid permeability was in error. The magnitude of this error was shown to increase as the permeability decreases; it is not particularly important when the permeability exceeds .5 millidarcy but it is very important in the

[20] Standard Practice for Determining the Permeability of Porous Media, Am. Petroleum Inst. Code No. 27, 1935.

[21] Klinkenberg, L. J., The permeability of porous media to liquids and gases: Am. Petroleum Inst. Drilling and Production Practice, pp. 200–211, 1941.

case of dense carbonate rocks such as those dealt with in this study. Thus, specimen ET 20-1, for example, has a permeability calculated from a helium test at $\Delta P = 5$ atmospheres of 98.0×10^{-5} millidarcies, while its water permeability is 5.0×10^{-5} millidarcies, a difference of over 1,900 percent.

Klinkenberg brought out [22] that many previous investigators had obtained lower K values with liquids than with gases in tests on the same specimens but in most cases had interpreted their results as evidence of clay swelling or adsorption. Indeed, considerable effort had been expended in trying to explain why the liquid results were low. In his experiments, Klinkenberg passed air, hydrogen, carbon dioxide, nitrogen, and iso-octane (a liquid) through Jena glass filters at various pressure differences and mean pressures. His results showed clearly that the flow of gas was not inversely proportional to the viscosity.

A second important contribution made by Klinkenberg resulted from his experiments in which he measured the volume of gas flowing through the filters at various mean pressures. It was shown that, as the pressure increases, the gas permeability decreases and approaches the liquid or "true" permeability. When the permeability is plotted against the reciprocal of the mean pressure, the curve is approximately a straight line; upon extending the plot to zero mean pressure reciprocal, equivalent to infinite pressure, the indicated permeability is practically identical with K_{liquid}.

Figure 2, reproduced from Klinkenberg,[23] indicates this approach to K_{liquid} as the mean pressure is increased. It will be noted also that the permeability values obtained with different gases are widely different at low mean pressures but approach a common value as the pressure rises.

From the preceding paragraphs it is evident that Klinkenberg's discoveries necessitated modification of the gas test procedure. It is still possible to determine the liquid permeability of a sample by running gas flow tests but instead of a single test at one mean pressure being sufficient, several are necessary to define the curve and the value "b" in Equation 2 so that the extrapolation to infinite pressure can be made.[24] In the present series of experiments, permeability determinations on most specimens were made at mean pressure values of 51, 41, 31, 21, and 11 atmospheres.

Klinkenberg's modification of Darcy's Law as applied to permeability determination using gases is based on the theory of slip and on the assumption that a porous medium is made up of a series of parallel capillaries to which the slip factor can be applied. Kundt and Warburg [25] showed that, when a gas is flowing along a solid wall, the layer of gas next to the surface is in motion with respect to that surface; that is, it slips. Hence the volume flowing through a capillary would be greater than would be expected from the Poiseuille Formula. The amount of slipping is proportional to the frequency of molecular collisions in the gas and hence to the mean free path. The rarer

[22] Idem, p. 200.
[23] Idem, p. 207.
[24] This is the procedure described in the current edition of Am. Petroleum Inst. Code No. 27.
[25] Kundt, A., and Warburg, E., Poggendorfs Ann. Physik, vol. 155, pp. 337 and 525, 1875; quoted by Klinkenberg, op. cit., p. 203.

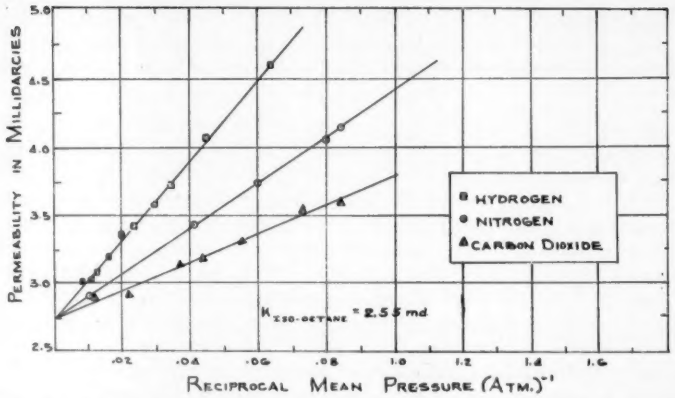


FIG. 2. (After Klinkenberg.) Permeability of core sample "L" to various gases and to isooctane (liquid). Note the convergence of the curves as the mean pressure increases and the close correlation between the extrapolated gas curves and the liquid permeability.

the gas, the greater the slippage and the greater the deviation from the Poiseuille Formula. Naturally, as the mean pressure is increased, the mean free path is shortened so that the slippage is reduced.

Considering porous media as collections of parallel capillaries, the correction to the Poiseuille Formula can be applied to Darcy's Law and Equation 2 is the result:

$$K = \frac{Q_m \mu L}{A(P_1 - P_2)} \cdot 1 + \frac{4C}{P_m R}. \qquad (2)$$

Here the factor C introduces the relationship between the mean free path and the mean pressure. Inasmuch as the average capillary radius, R, is not measureable, Klinkenberg lumped the entire correction into one constant, b, equal to $4\,C/R$. The most usable form of Equation 2 is:

$$K_a = K_{\text{liquid}}\, 1 + \frac{b}{P_m},$$

in which K_a = permeability measured using a gas,

K_{liquid} = the "true" permeability obtained by extrapolation to infinite pressure or determined by a liquid test.

In support of his conclusions Klinkenberg presents data showing that:

1. The K vs. $1/P_m$ curves for different gases passed through a specimen plot to the same value at infinite pressure.
2. This value is equal to the permeability as determined using liquid.
3. At the same mean pressure the permeabilities determined with different gases are different because the mean free paths are different but at mean pressures

at which the mean free paths of the various gases are the same, the permeabilities are the same.

4. Since "b" is inversely proportional to R (the average capillary radius), the value of "b" is small for highly permeable specimens but larger for less permeable ones.

The validity of Klinkenberg's correction has been verified by Muskat,[26] Calhoun and Yuster,[27] and many others in the petroleum industry. It was recognized by a revision of the American Petroleum Institute's Code No. 27.

N. C. Sen Gupta and M. G. Thein Nyun,[28] as a result of work entirely independent of Klinkenberg, arrived at strikingly similar results by somewhat different reasoning. They, too, noted that permeability test results varied when different gases were used and when a given gas was flowed at different pressures. Also, like Klinkenberg, they concluded that the slip factor was the source of the error and that therefore the mean free path of the gas was involved. Unlike Klinkenberg they applied the correction to the standard figures for the viscosities of the various gases, the logic being that the standard viscosity values as determined by the usual procedures cannot be applied without correction to flow through minute capillaries. Actually, the results are the same as it is simply a case of introducing a factor either early or late in the calculations. There is much to be said for the approach used by Sen Gupta and Thein Nyun although their work has not received credit from other workers in the field.

Acceptance of Klinkenberg's results was not universal. Grunberg and Nissan [29] reported tests in which they passed air, distilled water, 2% amyl alcohol, and NaCl solutions of .96 N and .614 N through Jena glass filters, and sandstone and oolitic limestone discs and were unable to get uniform values for the permeabilities of the different specimens. From their description the tests would appear to have been very exacting. The permeability coefficient varied for each liquid, and with each liquid it varied with the temperature. No correlation was found between gas and liquid permeability and the author's conclusion was that, not only viscosity, but also the density and the surface tension of the fluid and the average pore diameter and adsorptive power of the porous medium were involved.

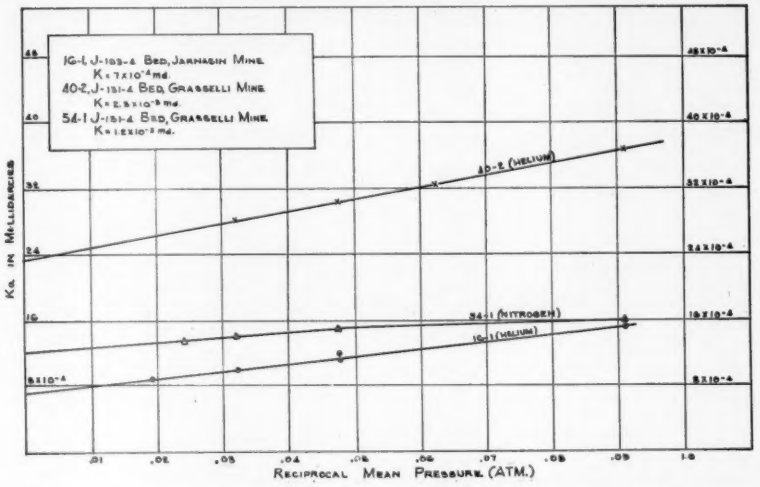
Considerable work has been done in an effort to reconcile the differences between Klinkenberg's results and those of Grunberg and Nissan. In general the agreement has been entirely with Klinkenberg; no one has been able to duplicate the effects noted by Grunberg and Nissan and they have not reported further work supporting their original conclusions. The revision of Code No. 27 indicates the acceptance of Klinkenberg's work by the petroleum

[26] Muskat, Morris, Discussion of Klinkenberg's paper in Am. Petroleum Inst. Drilling and Production Practice for 1941, p. 213.

[27] Calhoun, J. C., and Yuster, S. T., A study of the flow of homogeneous fluids through ideal porous media: Producers Monthly, vol. 11, no. 7, pp. 31–32; no. 9, pp. 25–27; no. 10, pp. 32–38; no. 11, pp. 22–27, 1947.

[28] Sen Gupta, N. C., and Thein Nyun, M. G., Fluid flow through porous media, Part 1, On the use of gases for the measurement of true permeability: Indian Jour. Physics, vol. 16, pt. 2, pp. 119–128, 1942.

[29] Grunberg, L., and Nissan, A. H., The permeability of porous solids to gases and liquids: Inst. Petroleum Technologists Jour., vol. 29, no. 236, pp. 193–225, 1943.


16-1, J-103-4 Bed, Jarnagin Mine
K = 7 X 10⁻⁴ md.
40-2, J-131-4 Bed, Grasselli Mine
K = 2.5 X 10⁻³ md.
54-1 J-131-4 Bed, Grasselli Mine
K = 1.5 X 10⁻³ md.
40-2 (Helium)
54-1 (Nitrogen)
16-1 (Helium)
Ka in Millidarcies
Reciprocal Mean Pressure (Atm.)

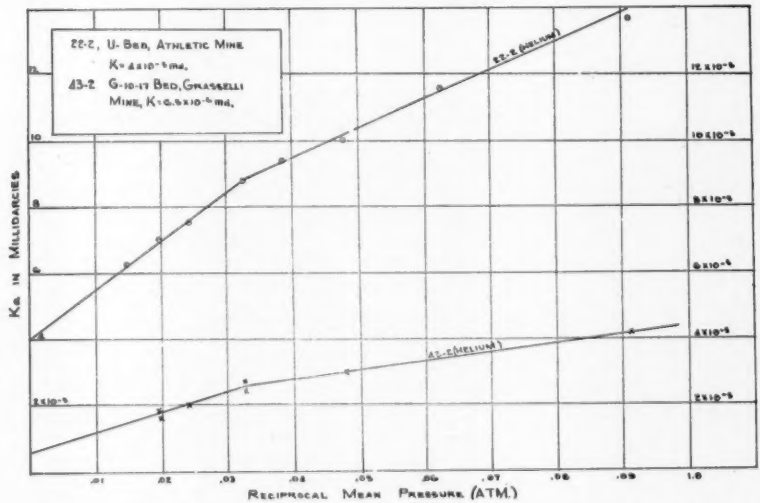

22-2, U-Bed, Athletic Mine
K = 4 X 10⁻³ md.
43-2 G-10-17 Bed, Grasselli
Mine, K = 6.5 X 10⁻⁴ md.
22-2 (Helium)
43-2 (Helium)
Ka in Millidarcies
Reciprocal Mean Pressure (Atm.)

FIG. 3. (Upper.) Typical K vs. $1/P_m$ curves of "recrsytalline" dolomites from the East Tennessee Zinc District.

FIG. 4. (Lower.) Typical K vs. $1/P_m$ curves of virtually unaltered limestones from the East Tennessee Zinc District.

industry. Only in the matters of adsorption of layers on the walls of capillaries and the variation in permeability with temperature has there been some agreement with Grunberg and Nissan. The argument as to whether or not important layers of fluid are adsorbed on the walls of rock intergranular spaces is still unsettled; the pros and cons of this question are discussed later in this paper.

The work on East Tennessee specimens gives a close confirmation of Klinkenberg. Permeability determinations on the same specimen using hydrogen, nitrogen, helium, and argon give widely different values at 10 atmospheres. As the mean pressure is increased, the values decrease in magnitude and approach each other. Extrapolated to infinite pressure, they are virtually the same. Also, the permeabilities determined at high pressures more closely approach the values obtained from liquid experiments. Figures 3, 4, and 5 show several typical K vs. $1/P_m$ curves for "recrystalline," limestone, and "original" dolomite, respectively.

In Figures 6 and 7 are plotted the permeabilities of Solenhofen limestone and East Tennessee "recrystalline" when measured under constant pressure differential but varying mean pressure. The lower values at higher pressure are as predicted by Klinkenberg. The tests on rocks do not give as precise checks on Klinkenberg's contentions as do his own tests on inert glass filters but, since the limestones and dolomites are neither perfectly homogeneous nor completely inert, this is not unexpected.

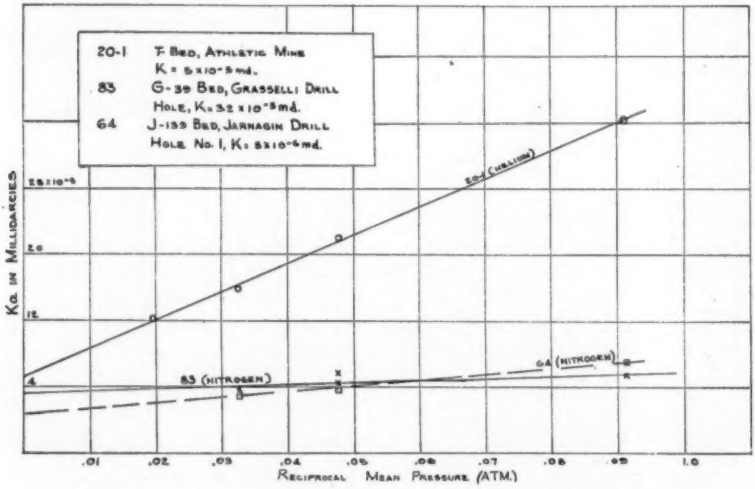
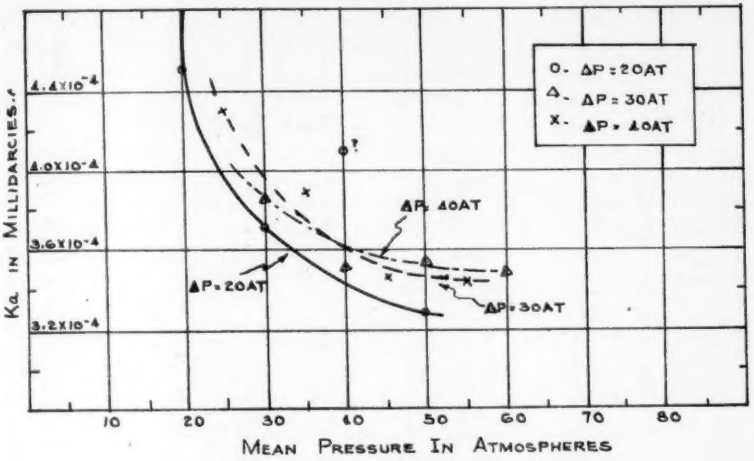


FIG. 5. Typical K vs. $1/P_m$ curves of "original" dolomites from the East Tennessee Zinc District.



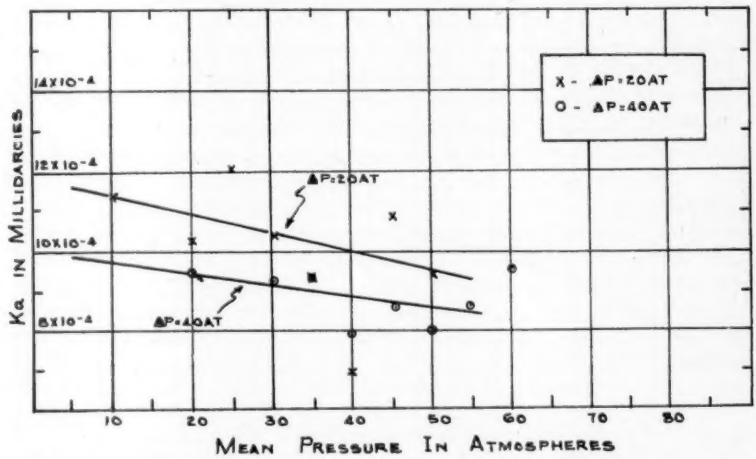
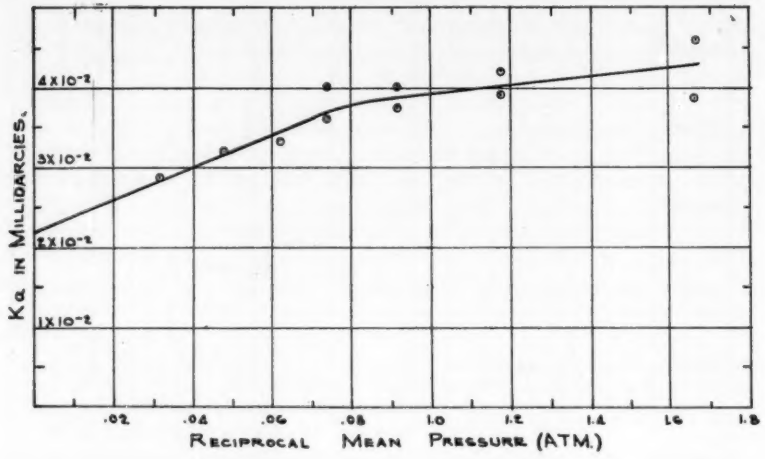


FIG. 6. (Upper.) Variation in the permeability of Solenhofen limestone to nitrogen at constant pressure difference but variable mean pressure.

FIG. 7. (Lower.) Variation in the permeability of specimen ET-24-2 to nitrogen at constant pressure difference but variable mean pressure.

The value of "b" in Equation 2 is not always constant; it increases with increasing pressure. This results in K vs. $1/P_m$ curves that are slightly concave downward. This variation was first noted by Klinkenberg who attributed it to the fact that the diameters of many of the rock pores are of



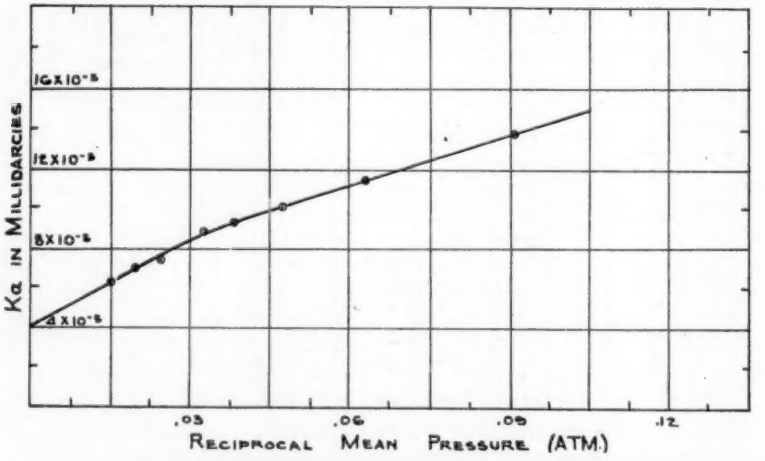


FIG. 8. (Upper.) Permeability of ET-12-1 (11) to nitrogen. The plot turns downward as the mean pressure rises above approximately 13 atmospheres. See Figure 10.

FIG. 9. (Lower.) Permeability of ET-22-2 to helium. The bend in the curve is at 30 atmospheres mean pressure. See Figure 11.

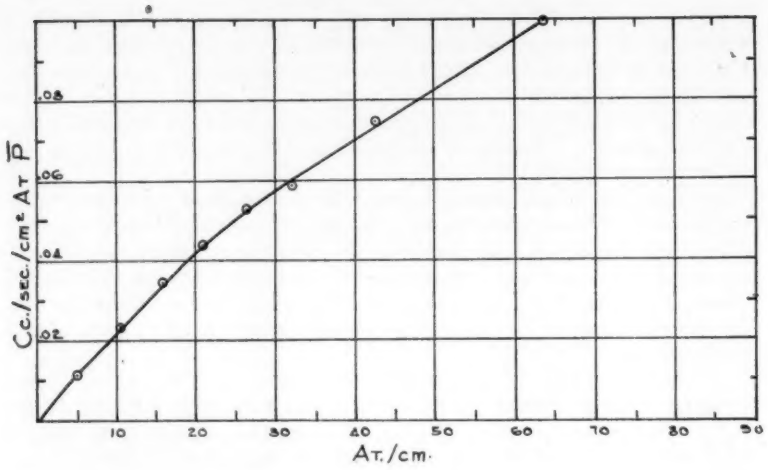
the same magnitude as the mean free path of the gas so that the theory of Kundt and Warburg can not be applied to them.[30] As the pressure increases, more and more pores are "large" relative to the mean free path; hence the slip factor is applicable to them and increases. An added factor is that in "a porous medium one is dealing with capillaries which vary in size throughout their length. Therefore as the mean pressure is reduced, a varying slip factor must be applied." [31]

Calhoun and Yuster present an extended discussion of the causes of the variations in "*b*" and note that the principal objection to Klinkenberg's explanation is that at low mean pressures "*b*" should be at a maximum whereas actually it is at a minimum. This cannot be accounted for by the slip concept. Yuster, separately,[32] has stated that although "we are not completely sold on the slip phenomenon . . . we have no adequate theory to explain the results obtained."

Many of the East Tennessee specimens gave K vs. $1/P_m$ curves similar in shape to those produced by Klinkenberg and Calhoun and Yuster (Figs. 8, 9). As the pressure rises, the slope is constant to a certain point; then it breaks downward and the plot follows another tangent. The extrapolation of the high pressure tangent to infinite pressure more nearly approximates the value of K as determined with liquid. The same is true in Klinkenberg's results. Klinkenberg has suggested [33] that the break in the curve is at the pressure at which the mean free path approximates the average diameter of the rock pores as at this pressure the change from Poiseuille to Knudsen flow [34] takes place in the maximum number of pores.

Grunberg and Nissan [35] likewise found that the permeability of their silica cores dropped at higher pressures. However, they attribute the greater flow at lower pressures to sub-viscous flow within the fluid which gives additional volume flux. The plots of flow vs pressure drop for many East Tennessee specimens suggest the presence of sub-viscous flow or some other factor which results in increased volume flux at pressures below 20 atmospheres. The plots are not straight lines extending to the origin. Frequently there are two "breaks" in the curves, one below 20 atmospheres and one at an intermediate pressure (Figs. 10, 11). The latter corresponds to the break in K vs. $1/P_m$ curve ascribed above to the change in the slip factor. The low pressure break and steep tangent indicate that there is something causing a more rapid flow rate per unit of pressure difference in this range than at higher pressures.

[30] Footnote 29, p. 204.
[31] Calhoun and Yuster, Footnote 27, no. 10, p. 36.
[32] Personal communication.
[33] Personal communication.
[34] This change is discussed at length in: Present, R. D., and Pollard W. G., On the self-diffusion of a pure gas through a long capillary when the mean free path is comparable to the capillary diameter: Phys. Rev., vol. 69, p. 53, 1946.
[35] Op. cit.



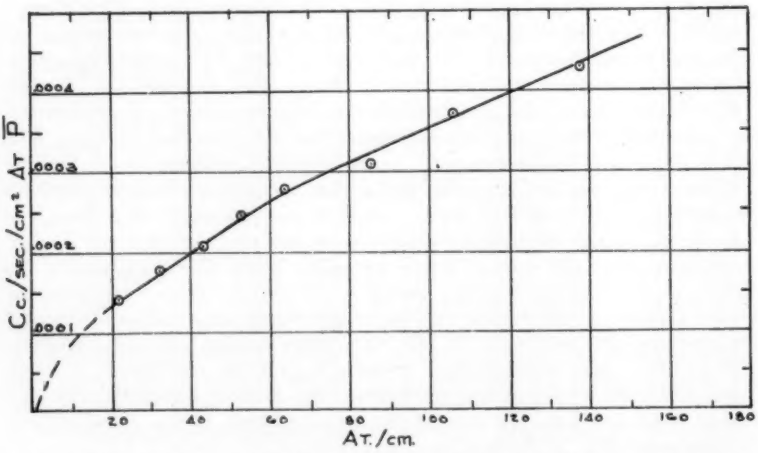


FIG. 10. (Upper.) Flow of nitrogen through ET-12-1 (11). See Figure 8.
FIG. 11. (Lower.) Flow of helium through ET-22-2. See Figure 9.

THE PERMEAMETER AND TEST PROCEDURES.

The apparatus was designed to do more than simply measure the permeability of a group of rocks. An additional objective was to test the theory of permeability in a range of K in which little work had been done and especially to determine whether relationships between liquid and gas flow that

had been established for sandstones and conglomerates applied to carbonate rocks in which the intergranular openings were much smaller and of a different shape. If it could be shown that gas and liquid flow tests yielded similar permeability values, future testing could be limited to the simpler gas technique.

None of the permeameters previously described was completely suitable for the problems at hand. The apparatus most widely used in the petroleum industry is designed to measure gas flow through relatively permeable rocks which transmit large volumes at low pressure in a short time. Modifications in either the pressure system or the measuring system would have been necessary before it could be used to measure dense limestones and dolomites. Rove's apparatus [36] likewise was limited to gas tests; while it was designed for testing rocks of permeability similar to those in the present study, it was limited to low pressure differences and, consequently, each test consumed a long time.

A number of factors combine to make a large number of tests necessary. First, the fact that when a gas is the medium, measurements must be made at several mean pressures as described by Klinkenberg [37] increases the number of tests three to four fold. Second, it is necessary to measure many discs from each bed or rock type as no one specimen is likely to be perfectly representative. Among others, variations due to non-uniform distribution of stylolites and dolomitization, or variations in grain size, are common. No bed is perfectly uniform throughout and an average of several discs is more representative than the measurement of a single specimen. Third, the need for constant vigilance against leakage around the specimen can be met in part by repeating a certain percentage of the runs.

An increased rate of flow can be achieved by increasing the cross-sectional area of the test piece, by reducing its thickness, by using a fluid of lower viscosity or a gas with longer mean free path, or by increasing the pressure difference. All of these were tried. The last method increases the flow most easily and effectively.

As the disc thickness now used is only one centimeter, no great decrease is possible without making the discs thin and fragile. It is desirable to keep the one-inch or one and one-eighth inch diameter because diamond drill cores are of this size and it is convenient to be able to use them.

The viscosities of all the common gases fall within a rather narrow range so no great flow variation is achieved by using the gas of lowest viscosity. There is of course a considerable time saving in using a gas instead of a liquid because of the viscosity difference. This is one reason why oil companies use air.[38]

The difference in mean free path between helium and nitrogen is nearly 300 percent and, next to pressure variation, the switch to the longer mean free path of helium is most effective in raising the rate of flow.

[36] Rove, Olaf N., op. cit., pp. 62–64.

[37] Klinkenberg's findings had not been published when Rove did his work.

[38] For other advantages of air over water see Muskat, Morris, The flow of homogeneous fluids through porous media, p. 92, New York, 1937.

Gas cylinders with pressure in excess of 100 atmospheres are readily obtainable. They are convenient to use. Pressure differences of 100 atmospheres per centimeter are sufficient to produce flow through most rocks at a convenient rate and the tests can be conducted easily and in a small fraction of the time needed when the flow is at a pressure differential of one atmosphere.

Accordingly, a permeameter was constructed so as to make possible:

1. Simple, expeditious measurements of the permeability of rocks with permeabilities in the range 10^{-2} to 10^{-7} millidarcies.
2. Permeability measurements using several different gaseous and liquid media interchangeably without removing the specimen from its holder.
3. Measurement of gas flow through the specimen when $\bar{P}$ was constant and ΔP was varied or when ΔP was constant and $\bar{P}$ was varied.

The gas permeameter consists of a gas tank (A), a valve and gauge block (B), a release valve block (R), a drying cylinder (C), the specimen holder (D), and the collecting assembly (E) as shown in Figure 12. The specimen holder is shown in detail in Figure 13.

All of the connections on the high pressure side of the system are made of 1/16-inch (inside diameter) heavy-walled copper tubing. The packing is of the "unsupported area" type described by Bridgman.[39] The intake valve, a, and the release valve, b, are of cone-in-cone construction. A 2,000-pound Bourdon tube gauge was used in all tests except those on very permeable specimens. For these, low pressures produced ample flow and a 200-pound gauge was used. The stem connecting the gauge to the gauge block has a cone-in-cone fitting with the block; the connection to the gauge is simply a standard male-female screw connection with a carefully machined seat which can be sealed with ordinary paint.

The drying cylinder has one-inch steel walls and a chamber 1½ inches in diameter and 12 inches long. It is filled with dehydrated silica gel or calcium chloride. In addition to assuring moisture-free gas for the tests, the cylinder serves as a storage tank to increase the volume of gas in the system so that the desired pressure can be maintained during flow without constantly admitting more gas from the tank.

The specimen holder is a stainless steel cylinder 3⅛ inches long, 2½ inches in outside diameter, and 1¼ inches in inside diameter at the point where the specimen rests. A 1/16-inch hole connects the chamber with the high pressure system; the low pressure side is fitted with a 1½-inch screw plug which, when removed, permits changing the specimen and when inserted acts in combination with the packing rubbers to effect the seal around the specimen. Two holes 1/16-inch in diameter penetrate the walls of the cylinder on each side of the specimen seat. During test runs these are closed by ¼-inch screw plugs sealed with paint.

Most of the test discs were one centimeter thick; about half of them

[39] Bridgman, P. W., The physics of high pressure, pp. 32–35, London, 1931.

were one-inch in diameter while the rest were 1⅛ inches in diameter. Discs of various lengths up to 1.5 centimeters and of any diameter up to 1⅛ inches can be accommodated simply by varying the length and thickness of the packing rubbers. Larger discs would require re-boring of the chamber. It is desirable to keep at least a ⅛-inch and preferably 3/16-inch difference in the diameter of the specimen and the diameter of the chamber; otherwise the packing rubber is so thin that it is difficult to handle.

Finding a method of preventing leakage around the specimen was of prime importance. A number of different methods of packing were tried. The

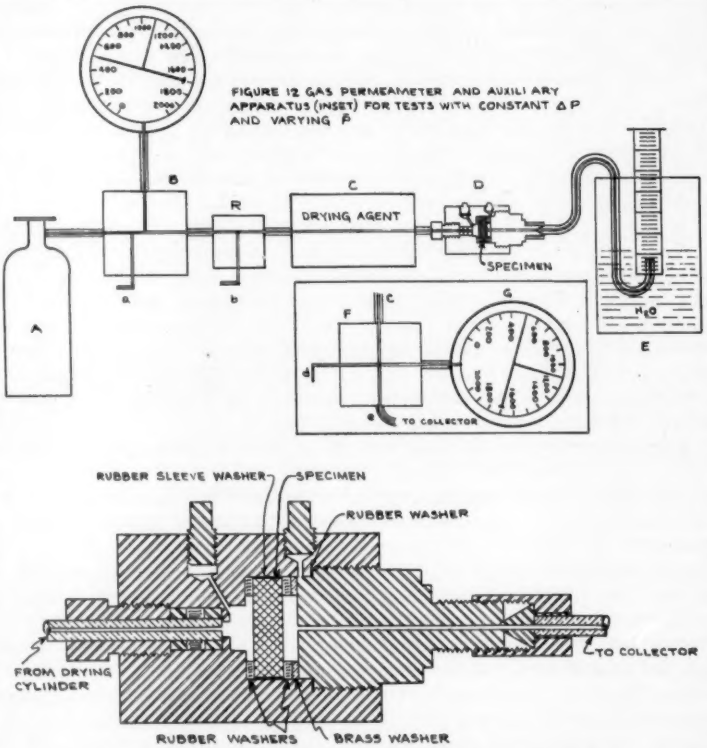


FIGURE 12 GAS PERMEAMETER AND AUXILIARY APPARATUS (INSET) FOR TESTS WITH CONSTANT ΔP AND VARYING P

FIGURE 13 DETAIL OF STAINLESS STEEL SPECIMEN HOLDER
SCALE 1"

method finally adopted consists of wrapping the cylindrical surface of the disc in several thicknesses of scotch cellulose tape and inserting it into the hole of a rubber sleeve washer cut to fit the specimen snugly. The outside diameter of the sleeve is 1¼ inches, just the size of the chamber. For best results, the length of the sleeve should be within a few thousandths of an inch of the length of the disc. Thin rubber washers of 1¼-inch outside diameter and $^{13}/_{16}$-inch inside diameter sandwich the specimen, the one on the high pressure side resting on a shoulder at the base of the chamber and the one of the low side adjoining one or more brass washers which separate the rubber from the face of the screw plug. Upon screwing in the plug firmly, the rubber sleeve washer around the specimen is compressed and squeezes the disc, thus preventing any flow except through the disc itself. The quality of the seal is indicated by the fact that when a glass disc was inserted and subjected to 100 atmospheres pressure, no measurable flow was recorded.

A thin rubber gasket serves as packing around the plug in the specimen holder. The external connection to the plug is of the cone-in-cone type. The tubing between the specimen holder and the collector is ¼-inch heavy walled rubber tubing which slips snugly over the end of the plug. A bent piece of glass tubing leads into the water tank and up into the gas burette or other graduated collecting vessel.

A 100 or 250 cubic centimeter graduate works very well as the collector in most tests. For smaller volumes requiring more accurate measurement, a gas burette with the small end sealed is used. Prior to starting a test, the graduate or burette is filled with water and inverted with the open end submerged in a battery jar of water. The volume of gas passing through the specimen is measured by measuring the volume of water leaving the collector as the gas is passed into its lower end. An electric wall clock to time the tests and a thermometer to indicate the temperature of the specimen holder and the water in the battery jar complete the apparatus.

Before inserting the specimen into the cylinder to start a test, the whole system is blown out with the gas to be used in the test to insure against contamination. After the specimen is sealed within the cylinder and the connection leading to the collector is secured, gas to the desired pressure is admitted by turning valve a, Figure 12. The gas passing through the specimen is allowed to escape until the flow is constant. Flow equilibrium is reached very quickly. Then the end of the glass tube is inserted into the end of the collector, the time and the level of the water column in the collector being noted. The length of time during which the gas is collected depends upon the rate of flow and in these tests varied from 30 seconds to several hours. Most of the specimens measured passed the requisite 5–250 cubic centimeters in a matter of minutes. As soon as a sufficient volume has been collected, the glass tube is removed from the mouth of the collector and the time of flow and the volume are noted.

Flow measurements are made generally with the pressure on the high side at 20, 40, 60, 80, and 100 atmospheres. At least two measurements are made at each pressure, the usual procedure being to start at 20 atmospheres and move in steps to 100 atmospheres and then release the gas in stages (by

turning valve b) while the second set of measurements is made. In this way the greatest number of tests can be made for the amount of gas consumed.

The pressure on the low side is assumed to be constant at one atmosphere. Standardization of the pressures at which readings are taken simplifies the calculations and makes possible the construction of graphs from which the permeability can be read directly as soon as the flow volume is known. Figure 14 is an example of these graphs. Variations in the regular schedule of tests are necessary for very permeable specimens and for very dense specimens. In some instances pressure up to 130 atmospheres has been necessary to give a measurable flow through very dense rocks. Readings at 5 and 10 atmospheres differential pressure are taken on the more permeable rocks.

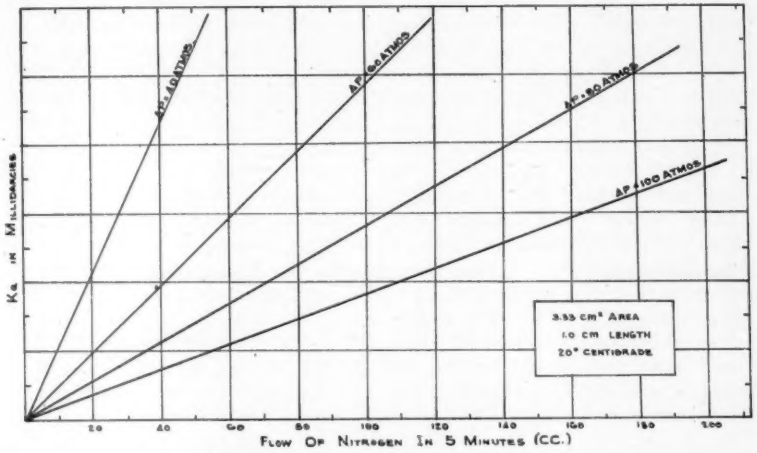


FIG. 14. Example of the graphs used for rapid calculation of permeability from flow results.

In general it is possible to scale or calculate the different permeability values as the tests are made. If the entire curve or any individual readings appear irregular, the tests are repeated. If, due to apparently abnormal flow volumes, a leak is suspected, the specimen is removed from the cylinder, reinserted, and the entire sequence repeated. About 10 percent of the specimens are re-measured as a matter of routine whether any irregularity is detected or not. This procedure guards against many of the possible sources of error. Almost without exception, the repeat tests have given results closely in accord with the original measurements.

To test a specimen with more than one gas, it is necessary simply to disconnect the gas cylinder and replace it with another. Then, after removing the small plug in the wall of the specimen block on the high pressure side, the system is blown with the new gas to replace all of the previous gas in the

system. After replacing the plug, gas pressure is applied and the new gas is allowed to flow long enough to flush out the specimen and the low pressure side of the apparatus. It is a great advantage to be able to change from one gas to another without having to disturb the specimen and its seal.

The auxiliary apparatus shown in the inset in Figure 12 is used when tests are run in which ΔP is kept constant while $\bar{P}$ is varied or in which $\bar{P}$ is maintained while ΔP is varied.

The connection, c, is substituted for the direct line to the collecting vessel, thus introducing gauge block F and gauge G into the system. The valve, d, controls flow through outlet, e, leading to the collector. By closing d while

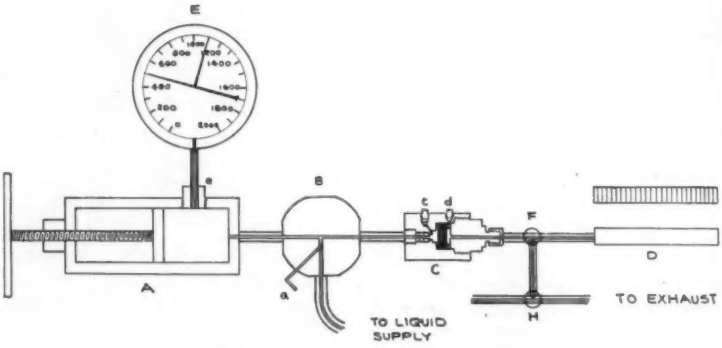


FIGURE 15 LIQUID PERMEAMETER

there is pressure on the high pressure side, any desired back pressure can be built up, limited, of course, by the prevailing pressure in the high pressure system. When the desired pressure is reached, valve d, which is capable of very close control, is opened to the point where the volume escaping is equal to the volume passing through the specimen. Collection and measurement of the flow are done in the same manner as described above.

The apparatus used for liquid flow experiments is shown in Figure 15. The pressure cylinder is the one described by Benedict.[40] It consists of a cylinder and a piston operated by a screw-jack. It is connected to gauge E and, through valve block B, to the specimen holder C. The specimen holder is the same as that used in dry gas tests. All connections are made of $\frac{1}{16}$-inch

[40] Benedict, Manson, Properties of saturated aqueous solutions of potassium chloride at temperatures above 250° C: Jour. Geology, vol. 47, no. 3, pp. 259–260, 1939.

bore copper tubing. Valve Block B permits the introduction of the test fluid into the system.

The low pressure side of the system consists of a three-way stop-cock, F, and a fine capillary with a volume of .0437 cubic centimeter per centimeter of length. The third stem of the cock connects to the exhaust pump and to the liquid supply via three-way stop-cock H.

In most cases liquid flow tests directly follow gas flow experiments without the specimen having been removed from the holder. This makes possible direct comparison of gas and liquid flow results without introducing possible errors in packing. The two sets of apparatus lie side by side and to switch from gas to liquid it is only necessary to remove the connection at the high pressure end of the specimen holder and attach the other piece of tubing leading from liquid pressure cylinder A (via block B).

The procedure for liquid tests is as follows: With the screw piston completely inserted and the gauge connection plug e removed, valve a is opened and the liquid allowed to flow into the system until it pours out of the hole at e. The gauge plug is then re-inserted. With valve a still open, the piston is screwed back, thus filling the cylinder with the liquid. Then valve a is closed and plug c is removed. Upon advancing the piston, liquid is forced into the remainder of the high pressure side of the system and all the gas is removed. Plug c is then replaced and 100 atmospheres pressure is applied. At the same time the low pressure side is connected to the exhaust pump. This situation is maintained for one hour so as to saturate the specimen with the test liquid. Then plug d is removed and stopcock H is turned so as to fill the low pressure side with liquid. Plug d is replaced and cock F is turned to connect capillary tube D to the system. At a given time the position of the meniscus in the capillary is noted. After sufficient time has elapsed for the meniscus to have advanced a few centimeters (the high pressure being maintained constant by continual turning of the screw jack), the time and the position of the meniscus are again recorded. From these data the liquid permeability of the specimen can be calculated.

It is possible to change from one liquid to another without removing the specimen. Plugs c and d and the gauge plug are removed and the system is blown out with compressed air to rid the system of excess test liquid No. 1. After the system is dry, the plugs are replaced and the new liquid is introduced and forced through the specimen until the disc is saturated with it. Then the test can proceed as above. Two liquids which are introduced consecutively should not react with one another or form a colloidal dispersion as this will result in erroneous determinations.

Although it is possible to follow gas tests directly with liquid flow tests, and this is the usual procedure, the reverse can not be done as successfully because of the difficulty involved in flushing the liquid from the disc. The gas flow increases as the specimen is dried out by the flow of dry gas.

Selection and preparation of the test specimens called for some care. The field specimens from which the discs were cut were rough blocks ranging from five to 25 pounds; the first ones collected were carefully oriented but when it became apparent that in massive beds the orientation of the disc with

respect to bedding, strike, and dip was of no consequence, this practice was discontinued. Specimens with pronounced layering or a profusion of stylolites, however, were cut in two directions, one parallel to the plane of stratification and the other perpendicular to it. Careful notation was made of the stratigraphic position of all of the specimens as well as their location with respect to ore and structural features.

Several different methods of preparing the test discs were tried during the course of the experiments. At first, a slab one centimeter thick was cut from the specimen and then the cylindrical disc was bored from it using a brass bit and carborundum. Later it was found to be more efficient to use a diamond drill bit in a drill press to core a plug from the hand specimen. Then discs of any desired thickness could be cut from the plug. Four or five holes two inches deep can be drilled in an average limestone or dolomite in an hour. Many of the field specimens were in the form of AX drill cores from which test discs could be cut with a diamond saw. Such specimens are prepared most easily. One disadvantage in them, however, is that knowledge of their relation to ore is usually less precise than in the case of mine samples.

SOURCES AND MAGNITUDE OF ERRORS.

Errors in the Test Procedures.

The extremes of permeability measured in this study were 2.4×10^{-2} millidarcies for a specimen of coarse crystalline dolomite and 6×10^{-7} millidarcies for a specimen of unaltered J–90–103 [41] limestone—a difference of some 4,000,000 percent. The variation in permeability from specimen to specimen of the same rock layer was much smaller although it frequently amounted to several hundred per cent. Since adjoining beds which were under comparison generally differed in excess of 10,000 percent, it was judged that refinements in technique which would have eliminated errors of less than 25 percent were not necessary, although all of the sources of error were investigated and evaluated. This decision greatly reduced the number of necessary readings during each test and made it possible to test more specimens of each bed and to make more check runs on each disc, thereby statistically improving the chances of correct average determinations for each bed.

[41] Three different numerical systems of bed identification are employed by the American Zinc Company in the three areas in which it is operating and an alphabetical system is used by the Universal Exploration Company. The correlation between the various numerical systems is given in A.I.M.E. Tech. Pub. 1818, by Oder and Miller. There are three numerical systems because the correlations between the three properties were not known when the geological work was started. The prefixes J, G, and M used in the text refer to Jarnagin Mine at Jefferson City, Grasselli Mine at New Market, and the Mascot Mine at Mascot, respectively. Thus G–10–17 bed should be read "Grasselli 10 to 17 bed." The numbers are especially useful because they indicate the distance in feet between the several units. Very commonly, in referring to a bed, only the number of the bottom contact is given; thus G–28–34 is known as the G–28 bed. In the Jefferson City area, the letters S, T, and U are used more commonly than the correlative numbers to designate the lower parts of the stratigraphic column. The positions of the lettered units are given in: Crawford, Johnson, Structural and stratigraphical control of zinc deposits in East Tennessee: Econ. Geol., vol. 40, pp. 408–415, 1945.

Over 1,000 permeability determinations were made on 146 test discs at various pressure differences and mean pressures and using different fluids. The fact that the results obtained are of the same order of magnitude as those obtained by Rove and others who have tested similar materials supports the contention that no major error has been made. The close agreement of permeability values resulting from tests on the same specimen under widely varying conditions, the intelligible plots of K vs. $1/P_m$, and the ability to reproduce results within narrow limits would further indicate that the figures are a sound basis on which to undertake geological reasoning.

Although the permeability obtained for each specimen is probably not the exact "absolute permeability" of the rock layer—if, indeed, there is such a thing as "absolute permeability" for a substance as variable as a geologic unit—it approaches that figure and certainly it is close enough to the true value so that the relative permeability of the layers and rock types can be stated with confidence.

Leakage is potentially the most important source of error and its prevention was the biggest problem in the experiments. Leaks generally cannot be detected by direct observation but must be deduced from the erratic nature of the flow.[42] They also become evident when the results cannot be duplicated.

After a few hundred experimental runs had been made, it was possible to predict with fair accuracy the permeability of a given specimen and any wide variation was rechecked by removing and re-packing the specimen and re-running the test. If the results still were unusually high, the specimen was thoroughly examined with a hand lens for minute cracks that might account for the variation. Then, two other discs cut from the same specimen were run. If they checked each other but not the first specimen, the erratic result was discarded; if all the results were erratic, the three were averaged as the rock was deemed to be of variable permeability. About ten percent of all the specimens were re-run as a matter of course a few days after the original test. In almost all cases, the original result was duplicated within a few percent.

The tightness of the packing system was checked by substituting a disc of plate glass in place of the usual rock specimen. No measurable flow occurred over a 24-hour period at 100 atmospheres pressure.

An error that occasionally approached or slightly exceeded 25 percent but usually was of lesser importance resulted from the variation in the inside diameter of the end packing rubbers. The maximum error was 28 percent. As the amount of pressure applied to the packing was not constant, there was a slight variation in the cross-sectional area of the fluid inlet and outlet. In many cases a slight discoloration where the rubber touched the specimen made it possible to measure the diameter which had prevailed during flow. In these tests the measured diameter was used in the calculations although the correction was not large.

[42] In a few tests, mercurochrome was put into water to stain the flow channels and give some idea of how the flow was distributed. In these tests, of course, leakage around the packing was readily detectable.

Sources of error which were evaluated and deemed negligible for the purposes of this study were:

1. The assumption of one atmosphere pressure on the low pressure side of the specimen rather than taking a barometric reading during each test introduced an error of less than one percent as the experiments were performed practically at sea level and the variation in barometric pressure did not exceed one inch of mercury.

2. The effect of the vapor pressure of the water which was displaced in the collecting vessel and above which the gas flow accumulated was slight. Of even less magnitude was the variation in this vapor pressure with changes in room temperature during long term experiments.

3. The gas expansion occurring as the gas warmed during accumulation was not great as the tests were of short duration generally. The cooling of the gas as it left the supply cylinder was counteracted by having a system of large volume relative to the volume passing through the specimen. Thus the temperature of the gas as it passed through the specimen and when its volume was read was essentially room temperature. As most of the tests occupied a matter of minutes only, there was no significant change in that temperature during the period between flow and measurement.

4. The viscosity of the gases used varies slightly with temperature. The assumption of 20° C as the prevailing temperature introduced a maximum error of two percent when the room temperature varied 10° C. The variation in gas viscosity with pressure also is of slight importance but, as it could be applied to the basic values entering into the calculations and thus did not involve extra calculations, the pressure correction was made. Below 20° C the viscosity error and the vapor pressure error (No. 2 above) were in the same direction and positive; below 20° C the two errors were opposed.

5. Instrumental and dimensional errors. Gauges and thermometers were checked against standards and were accurate within one percent. The volume and fineness of graduation of the collecting vessel were varied according to the volume passed so that a large volume was collected in comparison to the probable reading error. The capillary tube used as a collector in the liquid tests had previously been standardized by filling a measured length with mercury and comparing the weight with the weight of the tube when empty. All thickness and diameter measurements of the test discs were made with a micrometer.

6. In tests involving water, there is a possibility that dissolved air will form bubbles as the pressure decreases during flow through the specimen. Such bubbles might become trapped in the rock and block flow channelways so as to cause low flow measurements. To test the importance of this source of error, de-aired water prepared according to the method described by Casagrande and Fadum [43] was used in several tests in place of the boiled, distilled water usually employed. No important difference was noted in the

[43] Casagrande, A., and Fadum, R. E., Notes on soil testing for engineering purposes: Soil Mechanics Series, no. 8, p. 25, 1940. The method was devised by G. M. Fair.

permeability values obtained. The tests were run at 100 atmospheres pressure difference. Either there was no great amount of air in the boiled distilled water or there was sufficient driving "head" to sweep out any bubbles which tended to block the pores.

Causes of Variations Between Permeability Measurements Made With Liquids and Gases.

Most observers have recorded discrepancies between the permeabilities of materials as measured with dry gases and the permeabilities of the same materials when measured with liquids. This experience was repeated in several tests on East Tennessee specimens, the results of which are shown in Table 2.

One important source of this difference was eliminated by Klinkenberg when he showed that a slip factor should be applied to gas flow measurements. Some of the other factors which may cause a variation under natural conditions from the results obtained in gas tests in the laboratory are not so easy to evaluate. Under certain circumstances they may have sufficient importance

TABLE 2.

PERMEABILITIES OF EAST TENNESSEE SPECIMENS AS MEASURED WITH GASES AND VARIOUS LIQUIDS (MILLIDARCIES).

Spec. no.	Permeability measured with					
	Nitrogen	Argon	Helium	1·*N* NaCl	4·*N* NaCl	Water
12-2	9.5×10^{-3}		11×10^{-3}			6.8×10^{-3}
32-2	3×10^{-4}	3.2×10^{-4}	3.4×10^{-4}			2.4×10^{-4}
33-1	4.6×10^{-2}		5×10^{-2}			2.5×10^{-2}
48-2	1×10^{-3}		1.1×10^{-3}	4.6×10^{-4}	4.4×10^{-4}	4.5×10^{-4}
54-1	9.7×10^{-4}					4.9×10^{-4}

to raise a question as to the significance of gas flow test results. Some of these, such as clay swelling, adsorption, and surface tension effects, are related to the physical constitution of the rock or to reactions which occur between the rock and the solution; others are dependent on the character of the fluid in motion.

Although under ideal laboratory conditions the "absolute" or "fundamental permeability" of some rocks can be measured, such conditions are rarely if ever duplicated in nature. The flow of water or natural gas through clean quartz sand probably most nearly approaches the ideal condition but even with clean sand, when the fluid is a mixture of gas, petroleum, and water, it is inadvisable to accept gas-flow test results uncritically. Interactions between the fluids make flow prediction more difficult.[44] In the flow of a chemically vigorous ore-forming fluid through a reactive rock such as a limestone, the

[44] Muskat, Morris, Production research, present and future: Am. Inst. Min. Met. Eng. Petrol. Tech., vol. 1, no. 7, pp. 9–16, 1949.

permeability must be changing constantly so that during alteration the rock would have no "absolute permeability" except at a given instant. This is a large departure from "ideal" test conditions.

It is apparent from a review of the opinions of those closest to the problem that, ideally, the relative permeabilities of a group of rocks for a particular fluid should be determined by passing that fluid through the specimens. Thus Yuster says "From the foregoing discussion . . . it can be seen that the permeability of a porous medium depends upon the fluid used to measure it. Even with no reaction between the fluid and solid this will hold and it is especially true if a reaction occurs. . . . Since most oil sands will react with the aqueous liquids in contact with them, the practical permeability determination requires the use of those fluids." [45]

This, of course, offers little encouragement to the student of ore deposition who cannot be perfectly certain about the physical nature and chemical composition of the fluid with which he is dealing. Fortunately, although it would be ideal always to measure permeability with the particular fluid in question, it is not necessary to do so to obtain useful results. The majority of those studying permeability and daily making thousands of measurements of this property regard their results as close enough to reality to be of value. Recognition of the sources of error and application of the possible safeguards to prevent them, however, lessen the chances of serious error. A discussion of these factors follows.

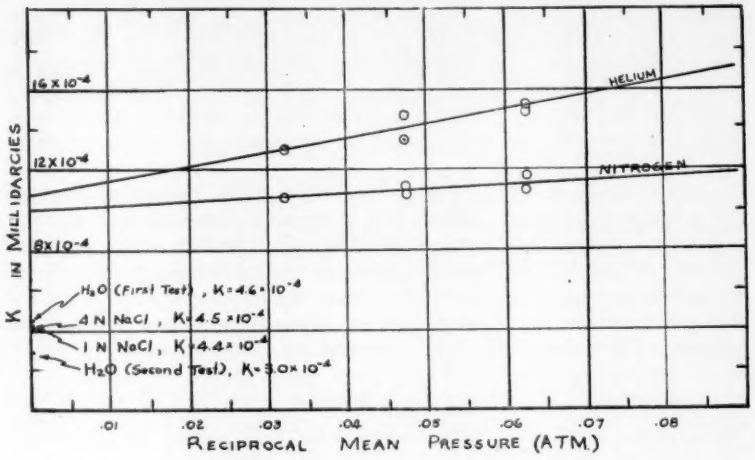
Clay Swelling.—It is obvious that swelling of clay particles distributed between the grains of a limestone or dolomite will result in a dimensional change in the pores and a decrease in the permeability. Clay minerals may take up large quantities of water and swell as they do so. As shown by studies of insoluble residues, most carbonate rocks contain a clay or silt fraction. These facts have been used frequently to explain the lower permeability obtained when certain rocks are tested with water than when they are tested with gas.

Johnston and Beeson have produced data showing a marked difference in the ratio $\frac{K_{\text{Fresh water}}}{K_{\text{Salt water}}}$ for cores on opposite sides of a contact between clean sandstone and sandstone containing much clay.[46] The $\frac{K_{\text{Air}}}{K_{\text{Salt water}}}$ ratio showed no marked change at the contact. They recommend the use of salt water solutions which impede clay hydration for tests on materials whcih show wide differences between K_{Air} and K_{Water}.

A specimen of "recrystalline" from the Grasselli U-bed horizon was tested with helium, nitrogen, distilled water, and salt solutions of 1 *N* and 4 *N* concentrations. The first water test was run before the salt solutions and the second water test was run last. The results are shown in Figure 16. The two gas tests gave a good check on each other but, as usual, the liquid tests

[45] Yuster, S. T., Homogeneous permeability determination: Producers Monthly, vol. 12, p. 40, 1947.

[46] Johnston, Norris, and Beeson, C. M., Water permeability of reservoir sands: Am. Inst. Min. Met. Eng. Tech. Pub. 1871, 1945.



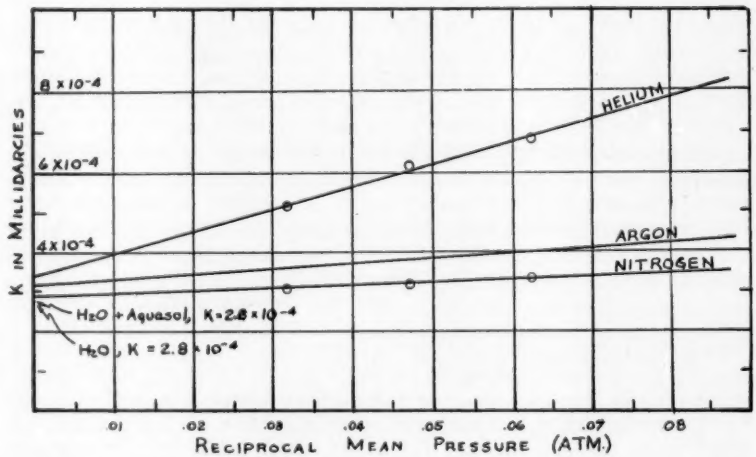


FIG. 16. (Upper.) Permeability of U-bed "recrystalline" specimen ET-48-2 to helium, nitrogen, distilled water, and 1 *N* and 4 *N* NaCl solutions.

FIG. 17. (Lower.) Permeability of "recrystalline" specimen ET-32-2 as determined with helium, nitrogen, argon, water, and water plus a wetting agent.

yielded lower values than the gas tests. The two salt solutions gave permeabilities close to that obtained in the first water test which may indicate that clay hydration is not the cause of the lower values found in the liquid tests. The fact that there is no great decrease in permeability with decrease in fluid

salinity, an effect noted by Johnston and Beeson,[47] also supports this conclusion. However, the result of the second water test, which was run subsequent to the salt tests, is considerably lower than any of the others and suggests that swelling may have occurred during the 51 hours of being saturated with liquid even though during much of this time the liquid was salt solution. Water had flowed through the specimen for three hours prior to the first water test.

Another series of experiments was run on a specimen taken from the same bed at the Jarnagin Mine. In this case water tests alternated with salt solution tests. The results are shown in Table 3. The first two water tests and the 1 *N* and .5 *N* NaCl solution tests gave almost identical permeabilities. The third water test, run the next day, again resulted in a drop in the volume flux. Between tests four and five the specimens sat overnight in .5*N* NaCl solution. The cause of the drop in permeability is not known.

TABLE 3.

SUCCESSIVE LIQUID TESTS ON U-BED "RECRYSTALLINE" FROM JARNAGIN MINE (ET 12-2)

Test no.	Liquid	Permeability (md.)
1	Water	4.28×10^{-3}
2	1 *N* NaCl	4.30×10^{-3}
3	Water	4.29×10^{-3}
4	.5 *N* NaCl	4.30×10^{-3}
5	.5 *N* NaCl	4.02×10^{-3}
6	Water	3.38×10^{-3}

Adsorption.—Adsorption of the test liquid or gas on the walls of the capillaries would reduce the dimensions of these openings and greatly reduce flow. Although the consensus of published opinion supports the belief that adsorption does take place, there are many who hold the opposite view. The following discussion of the relationship between permeability and adsorption, therefore, includes the arguments for and against the existence of important adsorption and the evaluation of the adsorption effect as proposed by those who acknowledge its importance.

The International Critical Table states:

"Adsorption of gases, vapors, and liquids at solid surfaces is dependent not only on the chemical natures and potentials of the adsorbents and the nature of the adsorbate but also on the physical state of the adsorbing surface. Perfectly uniform solid surfaces have as yet not been constructed. In general the surfaces of solids are composite, consisting of areas of different chemical potentials and adsorptive powers. Equations connecting the amount adsorbed and the chemical potential of the adsorbate hold only for the particular heterogeneous solid surface under investigation and are not rigidly applicable to other preparations of the same materials." [48]

[47] Johnston, Norris, and Beeson, C. M., op. cit., p. 9.

[48] Internat. Critical Tables of Numerical Data, Physics, Chemistry, and Technology, vol. 3, p. 250, New York, 1928.

Wentworth forced water through cracks in lava and found that the volume of flow decreased with time.[49] In some cases flow dropped to 1/1,000th of what would be computed by the Hagen-Poiseuille formula. The final establishment of equilibrium sometimes took several days. Tapping, pressure impulses, or other disturbance interrupted the decline but, on resuming steady flow, the decline started again. All liquids which would wet the rock surface showed the same effect. Wentworth attributed the effects to adsorption and states [50] that when the crack is narrowed to about .25 millimeter, the adsorbed film is thick enough to measure. The water film was calculated to be from .0124 millimeter to .0189 millimeter thick. An interesting conclusion is that the adsorbed layers will not become as thick in small openings as in larger ones but that their relative effect on the rates of flow may be as great.

Klinkenberg [51] and Calhoun and Yuster [52] are the principal students of permeability who deny the importance of adsorption in reducing the flow through rock pores. Klinkenberg reviewed the literature and decided that his survey led "to the conclusion that for flow through capillaries there is no evidence for the presence of adsorption layers of such a thickness as to decrease perceptibly the liquid permeability of a porous medium." [51] His results seem to bear out his conclusion. Using Jena glass discs so as to rule out swelling or erosional errors he passed kerosene, toluene, chloroform, diethyl ether, carbon tetrachloride, pentane, iso-octane, and nitrobenzene, liquids of widely different adsorptive character, through a set of four different filters. The permeability determined in each case was the same, within the limits of experimental error, and the results seem to deny important reduction in pore size by adsorption. Klinkenberg indicates that he would expect a rigid adsorbed layer several molecules thick to be sufficient to retard flow seriously.

Calhoun and Yuster worked with artificially prepared silica membranes. The flow of water, benzene, sodium chloride solutions, a complex wetting agent, a solution of stearic acid in benzene, naptha, and a crude oil in every case closely approximated that expected from calculations based on viscosity and pressure gradient.

These two series of experiments seem to have been performed carefully. It is difficult to reconcile them in the light of the studies reported below.

Grunberg and Nissan [53] concluded from tests on Jena glass filters similar to Klinkenberg's that the effective cross-section of the pores *was* different for different liquids due to differences in surface energy and consequent differences in the thickness of adsorbed layers.

Fraser advocates wall adsorption and says that "As grains become very small, the interstices become of such a size that the attraction of the water molecules adhering to the walls will extend across the channelway and conse-

[49] Wentworth, C. K., On the flow of liquids through thin cracks: Am. Jour. Sci., vol. 242, pp. 478–495, 1944.

[50] Idem, p. 493.

[51] Op. cit., p. 201.

[52] Calhoun, J. C., and Yuster, S. T., A study of the flow of homogeneous fluids through ideal porous media: Producers Monthly, vol. 11, no. 11, p. 23, 1947.

[53] Grunberg, L., and Nissan, A. H., The permeability of porous solids to gases and liquids: Inst. Petroleum Technologists Jour., vol. 29, p. 223, 1943.

quently there will be no free movement of water." [54] Since the hydrothermal theory requires the circulation of large volumes of solution, we might gather from this that small openings which restrict flow would be detrimental to the formation of ore bodies. This is contrary to Bain's suggestion [55] that adsorption is important in metasomatism and hence medium to fine grained rocks with greater surface area are more favorable to metasomatic replacement.

Hodgins, Flood, and Dacey carefully measured the flow of several permanent gases and condensable vapors through a fused pyrex plug.[56] The permanent gases gave straight line plots based on flow calculated from the Poiseuille and Knudsen equations; the flow plots of the condensable vapors, however, showed a falling off at about 50 percent of the saturation pressure and at low pressures the rates of flow were higher than predicted by the equations. Long term tests always resulted in flow equilibrium being established but hysteresis was noted as the pressure was raised or lowered. The authors' explanation of this seeming anomaly is based on adsorption. The falling off in flow rate is attributed to blocking off by the adsorbed layer and, for the excess flow over calculated, it is suggested that flow through the adsorbed layer may be responsible. It was not possible to measure the weight of the adsorbed layer on a sensitive balance.

Nutting [57] passed liquids through a capillary tube approximately one meter long and was able to measure the reduction in effective radius due to adsorption of an immobilized layer on the wall. In passing crude oil of approximately 40° API gravity through the tube, which had an internal radius of 0.4 millimeter, the flow gradually diminished until finally a steady state was established. The calculated reduction in radius and consequently the calculated thickness of the oil film was .0029 millimeter. Upon surrounding the tube with water, a further reduction of .0065 millimeter occurred which Nutting attributes to correlative adsorption of anions on one side of the glass and electropositive material on the other. One adsorption enhances the other through at least 0.1 millimeter of glass. Of thirty combinations tested, about half showed this effect but in no case was it greater than that of the oil-water pair. In all these tests care was taken to keep the moving fluid free of foreign matter which would plug the capillary and give an exaggerated result.

From his review of the literature, Ryder concludes that "it is a fact that under some circumstances relatively thick layers of immobile liquid may be adsorbed on pore surfaces, the size and number of passages available for the movement of liquid may be measurably reduced and consequently the effective permeability to some liquids may be lowered." [58]

The general literature of physics likewise accepts adsorption as an estab-

[54] Fraser, H. J., An experimental study of permeability with respect to ore deposition, unpublished thesis, Harvard University, p. 110, 1930.

[55] Bain, G. W., Measuring grain boundaries in crystalline rocks: Jour. Geology, vol. 49, p. 204, 1941.

[56] Hodgins, J. W., Flood, E. A., and Dacey, J. R., The flow of gases and vapors through porous media: Canadian Jour. Research, vol. 24-B, pp. 163–177, 1946.

[57] Nutting, P. G., Adsorption forces active through glass: Science, vol. 97, p. 74, 1930.

[58] Ryder, H. M., Permeability, absolute, effective, and measured: World Oil, vol. 128, p. 176, 1948.

lished fact and many processes and procedures are based on the relative ability of certain substances to adsorb gases and liquids.[59]

In a series of tests on Tennessee specimens, dry nitrogen was passed through a specimen of partially "recrystallized" brown limestone ($K = 2.7 \times 10^{-5}$ millidarcies) for a 24-hour period with readings being taken at odd intervals. No drop in the volume flux occurred during this time and all the readings were alike within the experimental error. Unless all the adsorption occurred within the two-minute interval at the beginning, during which the specimen was first saturated with gas, there was no appreciable adsorption of nitrogen.

Admittedly nitrogen is of low adsorbability and a liquid would no doubt build up a thicker layer on the pore walls. Tests of liquid adsorption in rock pores are difficult to make because the effect of clay swelling is unknown. Figure 17 shows the results of a series of tests in which helium, nitrogen, argon, water, and water plus a wetting agent were passed through a specimen of coarse "recrystalline" dolomite. During the water tests, the specimen was under flow for 25 hours but the final test yielded almost exactly the same permeability as the first. No growth of an adsorbed layer such as that described by Wentworth is indicated. All the adsorption must have occurred during the saturation period before the first test, with the steady state being reached almost immediately after the water first came in contact with the specimen. It is interesting that the addition of the powerful wetting agent did not affect the flow.

Although it cannot be proved that adsorption is a major contributor to the lower-than-calculated liquid flow, it may well be that such is the case. Bain gives the width of intergranular openings in relatively coarse Vermont marbles as ranging from .00000235 to .0000669 centimeter and the size of the pores in an unaltered limestone from East Tennessee as calculated from the slip correction is .000006 centimeter. Bain's figures [60, 61] are equivalent to 7.6 to 216.0 times the diameter of a water molecule and the pores of the fine grained limestone from Tennessee are 19.8 times that diameter. Obviously the .0124 to .0189 millimeter adsorbed water layers which Wentworth measured on the walls of cracks would block such tiny openings and their cohesive force would have to be overcome before any flow could occur. Increased "head" may flush out the adsorbed layers in the bigger openings but some pores are so small that even 130 atmospheres, the highest pressure used in the current series of tests, would not clear them. Thus the cross-sectional area of the effective channel is less than in gas flow tests and consequently the volume of liquid flow is less than would be calculated from gas test results.

Surface Tension.—Grunberg and Nissan suggested that the surface tension of the flowing liquid in addition to its viscosity would affect the volume flux.[62]

[59] See, for example, Emmett, P. H., and DeWitt, T. W., The low temperature adsorption of gases on glass and chabazite: Am. Chem. Soc. Jour., vol. 65, pp. 1253–1262, 1943. Arnell, J. C., Permeability Studies. I. Surface area measurements using a modified Kozeny equation: Canadian Jour. Research, vol. 24, Section A, pp. 103–116, 1946.

[60] Bain, G. W., Mechanics of metasomatism: Econ. Geol., vol. 31, pp. 505–526, 1936.

[61] Rove, O. N., op. cit., p. 61.

[62] Grunberg, L., and Nissan, A. H., op. cit., p. 223.

The experiments of Calhoun and Yuster mentioned above were designed to test this proposal. Solutions with surface tension values from about 30 dynes per centimeter (benzene, crude oil, and water plus a wetting agent) to 72 dynes per centimeter (water and sodium chloride solutions) were used. As there was no variation from the flow expected for solutions of the respective viscosities, Calhoun and Yuster concluded that surface tension did not affect the volume of flow.[63]

The tests on specimen ET 32-2 (Fig. 17) in which water was flowed first and then water plus the wetting agent, Aquasol,[64] seem to indicate that surface tension was not an important factor influencing flow in these rocks.

Streaming Potential.—When certain types of fluids are passed through porous media, a streaming potential is generated which opposes the flow producing it. The potential is dependent on the type of solid and fluid, the conductance and dielectric constant of the fluid, and the rate of fluid movement through the porous medium.[65] Klinkenberg found this effect when he passed nitrobenzene through a sintered glass disc; he corrected it by adding a small amount of ferric salt to the liquid, thus raising its conductivity.[66] The phenomenon would be at a maximum with pure water. Hence, permeability values measured using pure water should be somewhat less than those obtained with other liquids. Calhoun and Yuster believed that a streaming potential might affect their results but in general their permeability values for different liquids were in agreement.[67] Yuster noted that the importance of the streaming potential seems to increase with a decrease in permeability.[68]

In the case of the experiments on East Tennessee rocks, the effect of any streaming potential is negligible as distilled water and moderately concentrated sodium chloride solutions gave flow in inverse proportion to their viscosities. Since the ore-forming fluid is almost certainly highly ionized, streaming potential should offer no restraint to its circulation.

Concentration, Conductivity, pH, and Temperature.—Grunberg and Nissan found that permeability increased slightly as the concentration of solutions was increased. Using a glass membrane they found an increase in liquid permeability with .614 *N* and .960 *N* sodium chloride solutions over that obtained with water. The first showed an increase of 10 millidarcies (6.7 percent) and the second an increase of 15 millidarcies (10 percent) over the original 155 millidarcy water permeability.

Calhoun and Yuster likewise found the permeability increased with increased salt concentration though their percentage of increase was less than that found by Grunberg and Nissan.[69] As they have indicated, although sodium chloride was used in their tests, it is probable that other salts would show a similar behavior.

[63] Calhoun, J. C., and Yuster, S. T., A study of the flow of homogeneous fluids through ideal porous media: Producers Monthly, vol. 11, no. 11, p. 23, 1947.

[64] Produced by Phorex Laboratories, Inc.

[65] Yuster, S. T., Homogeneous permeability determination: Producers Monthly, vol. 12, no. 1, p. 38, 1947.

[66] Klinkenberg, L. J., op. cit., p. 201.

[67] Calhoun, J. C., and Yuster, S. T., A study of the flow of homogeneous fluids through ideal porous media: Producers Monthly, vol. 11, no. 11, p. 25, 1947.

[68] Idem, p. 39.

[69] Op. cit., p. 25.

Using a buffered solution, Calhoun and Yuster found a regular variation between the permeability of the cores and the pH of the test liquid. The minimum permeability was found at the neutral point while both acid and basic solutions yielded higher readings. The minimum reading checked the permeability values obtained using water and benzene.

Tests on silica glass cores to determine whether ionic concentration or electrical conductivity might vary regularly with the permeability showed that no such relationship exists. From their tests, Calhoun and Yuster have concluded that "whatever the anomaly, more than one factor is present. Neither the total ionic concentration, the conductivity, nor the pH value is the controlling factor alone." [70]

Grunberg and Nissan reported that the permeability decreased with increased temperature no matter what liquid they used. The decrease noted was .8 millidarcy per degree Centigrade.[71] Subsequent investigations have found no variation in permeability with temperature.

The above discussion may raise serious doubts in the mind of the reader as to whether gas permeability tests are of any value. Such is not the intention. In some districts, gas test results may not be used to calculate the liquid flow to be expected but in others the test results using either gas or liquid will probably be near enough to the absolute permeability for practical purposes. This was the case in East Tennessee where permeabilities measured with several liquids were lower than those from the gas tests but nonetheless were of the same order of magnitude and the relative permeabilities of the various rock types were the same regardless of the fluid used.

This local condition may not apply elsewhere. In other districts there may be a greater contrast between gas and liquid results and the contrast may be sufficiently greater in some beds than others that the relative order of permeability of the several beds is upset. Thus, the conclusions as to the relationship between permeability and ore distribution would be in error if based on gas tests alone. This emphasizes the necessity of making both gas and liquid tests on enough specimens to establish the reliability of the gas method.

The main purpose of the extended discussion is to enumerate the factors which are known or thought to influence permeability so that efforts can be made to determine their importance in local areas that come under study. Some of them, such as pH, ionic concentration, and conductivity, may never be major controlling factors but some of the others, such as adsorption and clay swelling, appear to be sufficiently powerful locally to have a marked influence on flow. A few observations at the outset of a study in a new area will indicate whether any of the interferences are important. If the gas and liquid tests give results that are in fair accord, then the bulk of the experiments can be conducted using the easier gas method.

Errors Resulting from Environmental Factors.

The question might be raised as to whether rock specimens collected in mines or taken from drill cores are sufficiently like rock in place to give signi-

[70] Op. cit., p. 25.
[71] Op. cit., p. 223.

ficant results in permeability tests. No positive conclusion can be reached since it is impossible for physical reasons to test these rocks in place for comparison with core or hand specimen results. Such evidence as is available suggests that there is no great change in rock permeability upon removing the rock from its original environment.

All of the mine specimens were solid chunks four to ten inches on a side and weighing between five and twenty-five pounds. In so far as could be observed with the naked eye, they were free of cracks due to blasting. In order to be certain that the results were not abnormally high due to the presence of tiny, incipient cracks, specimens of the same beds were taken from diamond drill holes outside the immediate mine area. A comparison of the results is given in Table 4. They indicate that the permeability of carefully selected mine specimens is probably not much different from that of the rock in place.

TABLE 4.

A COMPARISON OF THE PERMEABILITIES OF MINE AND DRILL HOLE SPECIMENS OF THE SAME ROCK LAYERS.

Spec. no.	Bed	Mine or drill hole	Permeability (millidarcies)
70	U-bed limestone	Jarnagin No. 1 Hole	1.8×10^{-6}
105	U-bed limestone	Jarnagin No. 2 Hole	4.4×10^{-6}
13	U-bed limestone	Jarnagin Mine	4×10^{-6}
25	U-bed limestone	Athletic Mine	1.5×10^{-5}
47	U-bed limestone	Grasselli Mine	3.5×10^{-6}
77	T-bed dolomite	Jarnagin No. 1 Hole	3.5×10^{-5}
108	T-bed dolomite	Jarnagin No. 2 Hole	2.7×10^{-3}
8	T-bed dolomite	Jarnagin Mine	5.3×10^{-5}
20	T-bed dolomite	Athletic Mine	2.5×10^{-5}
35	T-bed dolomite	Universal Mine	3.0×10^{-5}
46	T-bed dolomite	Grasselli Mine	3.0×10^{-6}

The permeability of specimen 108 is much above the average for the "original" dolomites [72] in the Tennessee district and would appear to be in error although two discs gave approximately the same result. Examination of the specimen revealed a sugary texture. This contrasts with the usual fine grain of such specimens and the larger grain size probably accounts for the anomalous permeability.

As previously mentioned, there are standard procedures for determining the permeability of aquifers from well flow tests as well as the usual laboratory methods. Field tests are preferred because the rock is in place and because a larger cross-section of the bed is tested than could ever be brought into the laboratory. But, provided proper care is taken, laboratory tests will duplicate the field results.

Similarly in the petroleum industry, there is a fair check between oil field performance and predictions based on hundreds of permeability tests on core samples. The greater number of variables involved, especially the multiphase character of the fluid, makes the accuracy of these predictions less perfect than those involving ground water. Nonetheless, they are sufficiently useful to make permeability tests of oil sands standard practice.

[72] The rocks called "original" dolomites are described in Part II under *"original" dolomite.*

Two important factors of rock environment which are not duplicated in any of the standard permeability procedures are temperature and confining pressure. Increase in temperature causes most minerals to expand. The coefficient of expansion varies from mineral to mineral and in different directions in the same mineral. Hence, heating a rock must tend to create new openings due to differential expansion of the grains. This force would be especially strong in rocks containing several minerals with different expansion coefficients as Brown has pointed out in discussing possible causes of increased porosity at Balmat where calcite and diopside are prominent constituents of the host rock.[73]

While heating a rock undoubtedly puts it under internal strain, serious doubts arise as to whether the expansion tendency of the individual grains will increase its porosity when the rock is deeply buried. Strong forces oppose the expansion. One of these is the cohesive strength of the rock due to the interlocking character of the grains or to cementation. Much more important is the confining pressure which is related in magnitude to the depth of burial and the dynamics of the environment in which the rock is located at the time of temperature rise. Since hydrothermal ore deposits were formed at depths ranging from a few hundred to many thousands of feet, the static load of the overlying rocks is always considerable and often very great. In some areas great compressive stress resulting from diastrophism or nearby intrusion may be active at the critical time. These forces oppose any increase in rock vloume due to thermal expansion and tend to eliminate open pores and increase the rock density. It seems not unlikely that the confining forces would dominate. If this is true, any thermal expansion of the mineral grains would work toward the elimination of open spaces rather than their creation. The first expansion would be at the expense of the existing pore spaces.

In the course of developing a packing arrangement which would withstand the desired pressure, a series of results were obtained which show the effect of pressure on rock pore spaces and permeability. Instead of the packing around the specimen which is described on page 688, the test disc was fitted snugly into a rubber jacket which in turn fitted snugly into the cylinder. The rubber jacket was slightly longer than the test disc. Upon screwing in the plug, a steel ring was forced against the rubber jacket, compressing it and forcing it to squeeze the rock disc. The packing was most efficient in preventing leakage but the squeeze on some specimens caused a complete reversal of the slope of the K vs. $1/P_m$ curve. Under the confining pressure, a specimen of coarse limestone from Hanover, New Mexico, gave permeabilities of 6.2×10^{-5} millidarcies and 2.5×10^{-5} millidarcies at 80 and 40 atmospheres, respectively, whereas with the packing scheme later devised the figures were 3.9×10^{-5} and 8.4×10^{-5} millidarcies, respectively. This last relationship, in which the permeability is lower at higher pressure, is of course the normal one. Other rocks showed similar responses to the strong peripheral squeeze.[74]

At greater and greater depths beneath the earth's crust, the forces tending

[73] Brown, J. S., Porosity and ore deposition at Edwards and Balmat, N. Y.: Geol. Soc. America Bull., vol. 58, pp. 532–533, 1947.

[74] Since the ends of the disc were open, the system was not a perfect duplication of natural load conditions.

to close rock openings are increasingly great. Adams' experiments indicated that small cavities may exist in granite to a depth of at least 11 miles and Bridgman has concluded that minute crevices at least large enough to permit percolation of liquids can exist in the stronger rocks at pressures of 6,000–7,000 kilograms per square centimeter, corresponding to a depth of about 20 kilometers.[75] Openings in carbonate rocks would disappear at much shallower depths because of the greater ease with which these rocks flow under pressure. At a depth of several thousand feet, however, openings even in carbonate rocks can exist over long periods of time.

Summation of Data on Errors.

Investigation of the various sources of error indicates that the important ones have been met. None of the rest amount to more than a few tens of percent and some of them compensate for each other. The existing errors in the results are far less than the variation in permeability from specimen to specimen or from one rock type to another.

The solution of the leakage problem, which is potentially the largest source of experimental error, is described on page 688; the other errors in the test procedures proved to be minor. As a number of factors have been proposed as causes of the observed differences between gas and liquid permeability measurements, an extended discussion of these factors is given on pages 695 to 703. In local areas the composition or texture of the rocks may be such that one or more of these factors, such as adsorption or clay swelling, will dominate the flow through the rocks. In East Tennessee, the experiments have shown that gas tests may be used, without great error, in predicting the flow of liquids. In other districts it will be necessary to make a few observations at the beginning of the study to determine whether any of the interferences are important. When the gas and liquid test results are in good agreement, the easier and faster gas method will be found to be more convenient to use.

The evaluation of errors resulting from environmental factors is difficult because some of the characteristics of the rock environment cannot be duplicated in the laboratory. Certain tests indicate that high confining pressure will influence a rock's capacity for flow so that laboratory permeability measurements by the method described here probably are not an accurate indication of the permeability available to an ore solution circulating at great depth. However, in the case of those ore deposits formed at moderate or shallow depth, of which the deposits of the Mississippi Valley Type are important examples, it is believed that the relative permeabilities of the beds are essentially as they were at the time of ore deposition.

The experiments show that drill cores and mine rock samples of the same beds give comparable results.

(To be concluded in next number)

[75] Adams, F. D., An experimental contribution to the question of the depth of the zone of flow in the earth's crust: Jour. Geology, vol. 20, pp. 97–118, 1920. Bridgman, P. W., The failure of cavities in crystals and rocks under pressures: Am. Jour. Sci., 4th ser., vol. 15, pp. 243–288, 1918.

ALPINE LEAD–ZINC ORES OF EUROPE.

HENRY L. JICHA, JR.

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ABSTRACT.

The ore deposits of Cave di Predil (Raibl), Mezica (Miess), and Bleiberg-Kreuth, in Italy, Yugoslavia, and Austria, respectively, are representative of the Alpine lead-zinc ores of Europe and are of the "Mississippi Valley" type. In each case the upper 50 to 100 meters of the mid-Triassic (Wetterstein) limestone constitutes the chief ore horizon. The ore is in fissure veins and replacements, partly widely disseminated, and generally the bodies are not far below a relatively impervious formation (e.g., the Carditas or Raibl slate). Overturned anticlines (Mezica) and especially tear faults controlled mineralization.

Besides the usual galena, sphalerite, marcasite, dolomite, and calcite mineralization, the ores contain fluorite, barite, chalcopyrite, and some arsenopyrite, together with noteworthy quantities of wurtzite. Wurtzite shows botryoidal, concentric bands, in part alternating rhythmically with marcasite and forming the so-called "Schalenblende" of German geologists. Much of this wurtzite is markedly anisotropic, in part converted to sphalerite but most stable where darker in color and richest in iron (Ehrenberg's theory). Where light yellow it was either first formed as sphalerite or has now inverted to that mineral. Disseminated zinc sulfide, however, was apparently sphalerite when first deposited, and a later, cross-cutting sphalerite can also be distinguished, though the possibility is not excluded that all the zinc sulfide was at first wurtzite. The darker bands of the "schalenblende may have derived their iron by primary resorption from the associated marcasite.

INTRODUCTION.

In 1937–38 Dr. Charles H. Behre, Jr., made an extensive tour of the lead-zinc deposits of Europe. In the course of his studies of the deposits he acquired a large suite of ore specimens from each deposit. He provided the writer with the specimens and considerable other data collected at the time in order that a detailed paragenetic investigation might be made. Results of that study are here reported.

Three districts were chosen for this study because of their relatively close proximity to each other (within 100 miles), their geologic similarity, and their apparently related modes and times of deposition. These are Cave di Predil (Raibl) in Italy, Mezica in Yugoslavia, and Bleiberg-Kreuth in Austria.

ACKNOWLEDGMENTS.

Grateful acknowledgment is extended Professor Behre, for his advice and guidance in this study; and to Professors Paul F. Kerr, Walter H. Bucher and J. Lawrence Kulp, all of the Department of Geology, Columbia University, for their helpful suggestions and advice on some specific problems; and to the graduate students of economic geology at Columbia University, whose discussion, interest, and suggestions have also greatly helped in preparing this paper.

GENERAL DESCRIPTION.

The Bleiberg-Kreuth District is located in Western Carinthia (South-central Austria) about 12 km west of Villach and 50 km west of Klagenfurt, in the eastern end of the Gailtal Alps. The Mezica (Austrian name, Miess) district is located in Slovenia, Yugoslavia, in the eastward extension of the Carinthian Alps. The Cave di Predil (Austrian name, Raibl) mines are near the town of Raibl, in the Seebach Valley, Italy, about 8 km south of the Austro-Italian border and 16 km south of the Bleiberg-Kreuth District. Before World War I these three districts were all in the Austrian province of Carinthia (Fig. 1).

The rugged glaciated peaks and U-shaped valleys surrounding the districts are typical of the topography found throughout the southern Alpine region of Europe. Average relief is about 1,000 meters and the average elevation of the valley floors ranges from 500 to 1,000 meters.

All three deposits have a long history of development. The Cave di Predil mines have been known since Roman times and have been worked since the Fourteenth Century. Some of the Mezica mines have been worked since the Fifteenth Century and documents show that the Bleiberg-Kreuth area has been a lead producer since A.D. 1004.

GEOLOGY.

The lead-zinc deposits of Carinthia occur in fissure enlargements or other cavities in close genetic connection with soluble rocks, particularly limestone. Locally they constitute replacement bodies. These are a typically developed form of deposit, similar in many ways to the "Mississippi Valley" type of the

United States. Deposits of this kind traverse Carinthia in a broad east-west zone and are usually below an impermeable slate bed. The "Hauptschieffer," the Bleiberg or Raibl slate of the Upper Triassic, and the Werfen slate of the Lower Triassic all are such units. The ore deposits seem to be localized by the overlying argillaceous rocks (3).[1]

The three deposits under discussion fit the above general description of the Carinthian ore deposits very well. The stratigraphic environment of these ore deposits is similar. In each case, the ore-bearing horizon is the Wetter-

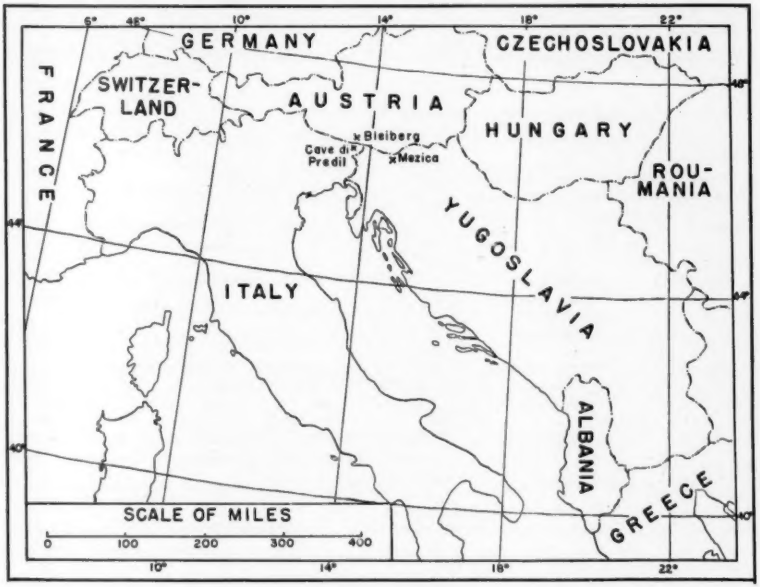


FIG. 1. Map of southern Europe showing the locations of the ore deposits discussed.

steinkalk, a limestone of upper Middle Triassic age. The ore deposition appears to have been at least partially controlled by the impounding effect of the overlying Raibl or Carditas slates. This control is demonstrated by the fact that the ore deposits invariably occur within 50 to 100 m of the top of the Wetterstein limestone and that, while ore may often appear in the basal member of the slates, the mineralization never extends any great distance into the shale layer, nor is there any mineralization found above this bed in areas where the Wettersteinkalk is mineralized.

[1] Numbers in parentheses refer to Bibliography at end of paper.

A generalized stratigraphic section for the three districts is given in Table 1 (5, 17, 20).

The overall structure of each of these three districts is different, but in a general way, the structural control of the ore deposition in each of them is the same. The ore occurs in fissures and tear faults, and along bedding planes in areas where there has been bedding-plane movement. The intersections of fractures or faults and planes of movement between beds are particularly favorable for ore deposition. Some replacement ore bodies also occur.

At Cave di Predil (Fig. 2), tear faults are the main structural features. Their close connection with the ore deposition is made clear by the fact that ore occurs only near and in these faults and mainly in an area bounded by the two major tear faults (the Fallbach and Barenklamm faults) running roughly

TABLE 1.

GENERALIZED STRATIGRAPHIC SECTION OF THE CARINTHIAN REGION.

Age	Formation	Description
Quaternary		Talus, glacial deposits, etc. (Missing in many areas)
Tertiary		Limestone conglomerates (Mezica)
Triassic		
Upper	Hauptdolomit (Main dolomite)	Dark brown to black dolomite 31.5–5,000 m.
	Carditas or Raibl slates	Black slates 15–500 m.
Middle	Wettersteinkalk (Ore-bearing limestone)	Chiefly limestone and dolomite; some shaly and marly beds in upper 30 m. 1,000 m.
	Muschelkalk	Various formations, including mostly marls and limestones and dolomites (Werfen and Buchenstein beds, etc.)
Lower	Notsch Carbon (Bleiberg) or Werfen schists (Raibl, Mezica)	

Paleozoic rocks are found in some areas

north-south, across the major structural trends of the Alpine arc. Faulting outside the mineralized area is less marked. At Bleiberg (Fig. 3), the overall structure is a graben, formed by the downfaulting of a large syncline parallel to its length. This graben is split by a large, high-angle thrust or tear fault (the Dobratsch thrust), whose lateral movement has caused the minor faulting with which the ore deposits are associated. The minor faults and bedding-plane movements at Mezica (Fig. 5) are related to overturned anticlines. In the Mezica district, the structural highs of the anticlinal axes are additional features controlling ore deposition.

The ores themselves are similar in composition. In general, the predominant gangue minerals are calcite and/or dolomite, and barite. Fluorite and anhydrite, though generally present in minor amounts, are the only gangue minerals present in some parts of the Bleiberg-Kreuth district. The ore min-

erals are galena, sphalerite, and wurtzite, with insignificant marcasite, pyrite, and arsenopyrite. Except at Mezica, the predominant form of zinc sulfide is wurtzite. Even at Mezica there is evidence that the zinc sulfide was deposited as wurtzite and inverted to sphalerite, the more stable mineral. At Bleiberg and at Cave di Predil the wurtzite has a botryoidal banded texture, characteristic of similar ores in many of the other European deposits. This form of the mineral is the "Schalenblende" of the German geologists. Secondary minerals, predominantly cerussite, anglesite, smithsonite, hydrozincite, calamine, wulfenite, limonite, and gypsum, were found in the upper oxidized zone of the deposits. Such ores have now, for the most part, been mined out.

The ratio of lead to zinc in the ores is a characteristic peculiar to each deposit. At Bleiberg-Kreuth the ratio is 10:1, at Mezica 2:1, and at Cave di Predil 1:4.

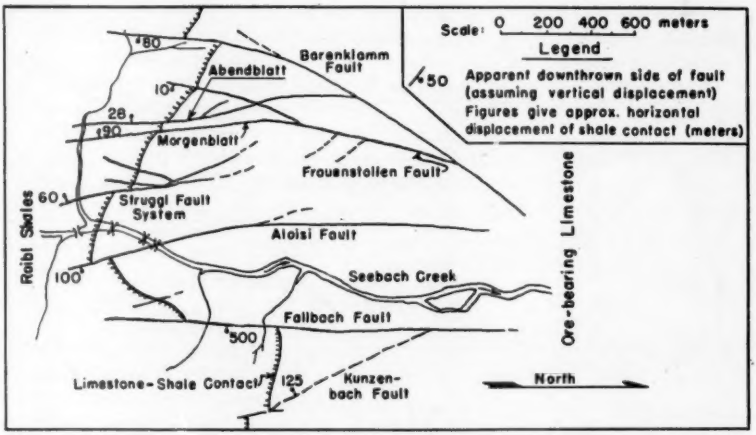


FIG. 2. The fault system at Cave di Predil (Raibl). After Radcliff (modified).

In origin these deposits are all closely related to each other in time and source, despite the slight differences between the opinions expressed by various investigators. All were associated with some deep-seated igneous mass. Evidence is furnished by the granite porphyry intrusives found at Raibl, which are of post-Jurassic, probably Tertiary age (21). The Tertiary age of the mineralization in all three districts is not disputed, but the exact times proposed vary. Tornquist (20, p. 90) gives the age of the Bleiberg-Kreuth deposits as Miocene-Pliocene. Di Colbertado (5, p. 288) considers the mineralization at Raibl to have taken place in late Oligocene and early Miocene time. The age of the Mezica deposits is given merely as Tertiary (10, p. 83–91). However, it seems reasonable to assume, as Di Colbertado (5, p. 288) has stated, that the hydrothermal solutions are related to a deep magmatic

mass associated with the intrusive manifestations of the peri-Adriatic Alpine arc.

ORE DEPOSITION AND PARAGENESIS.

Bleiberg-Kreuth.

The ore deposits at Bleiberg-Kreuth belong to the mesothermal or epithermal class, more probably the latter. The mineralization appears to have occurred in several phases, with little apparent discontinuity, except in the final phase, which was probably appreciably separate from the others in time.

The first phase was calcitization on a large scale. The original limestone was brecciated and recemented, with replacement veining, by introduced carbonates. In the second phase, minor amounts of pyrite (the first sulfide) and barite were deposited, closely followed by the introduction of yellow zinc

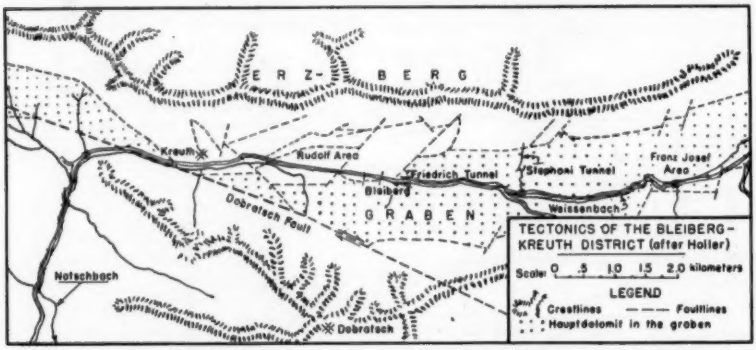


FIG. 3. Tectonics and ore deposition of the Bleiberg district (after Holler).

sulfide, probably as sphalerite, and later galena, which formed large euhedral crystals. A second carbonate phase that formed large scalenohedral crystals then took place. In the fourth phase the solutions were probably more acid and bright orange blend (wurtzite), botryoidal blend (schalenblende), barite, and marcasite were introduced, closely followed by fluorite. The marcasite occurs in large bladed masses that form incrustations on galena and other early sulfides and replace the late barite. Fluorite is the latest of all minerals. It is only a relatively minor accessory in most parts of the mines, but in some areas it makes up the chief gangue mineral. Cockade ore, made up of botryoidal blend around crystals of galena, with accessory barite and marcasite, appears to float in massive fluorite. It is noteworthy that fluorite is more startling in this limestone district than in others where dolomitization has been more conspicuous. For lack of adequate specimens it has been impossible to place the next two stages of the mineralization accurately. In some places anhydrite forms the chief gangue mineral and cements not only the brecciated limestone but also fragments of sulfides which were broken by

tectonic movements following directly upon or contemporaneous with the sulfide deposition. This tectonic effect is expressed in ores from all parts of the district, at least by minor shearing in the galena. In the areas of greatest stress the stages include brecciation and later recementation by finely crystalline anhydrite. Pyrite was deposited as the top layer on the late brown schalenblende. The last phase was another introduction of calcite, which in some cases penetrated the ores and caused secondary growth of the early scalenohedra, but for the most part formed only a coating of tiny scalenohedra on the pyrite shell of the schalenblende.

Description.

Carbonates.—Calcite occurs in three generations. The earliest generation is pre-ore, and permeated and recemented the fractured and brecciated bituminous limestone in which the deposits were formed. In some cases it replaced the original limestone with rhombohedral crystals of epigenetic carbonate. Large rhombohedral and scalenohedral crystals of the intermediate generation were introduced after the first phase of sulfide mineralization, partially replacing all the previously formed minerals. These were in turn replaced by the later sulfides and gangue. The last generation of calcite was introduced as the final stage of the mineralization sequence. This generation, in addition to forming scalenohedral crystals, most of which were of much smaller dimensions (1–2 mm in diameter) than those of the second generation, contributed to the secondary growth along the crystal faces of the second generation of calcite. This is demonstrated by replacement of the schalenblende along the faces of the second spar generation around which the zinc sulfide was originally deposited.

Iron Sulfides.—Marcasite and pyrite occur throughout the ore deposit. Pyrite was formed either in one or two generations. Euhedral and subhedral crystals of pyrite in masses of early calcite and limestone are thought to be an early generation although no evidence of the relative age of these pyrite crystals is found except on the basis of general paragenetic sequences. The second generation of pyrite, which forms a capping shell on the late schalenblende, is the last sulfide deposited. The only later mineral is calcite.

Marcasite was deposited during the third (apparently more acidic) phase of sulfide mineralization. It takes the form of thin peripheral bands of anisotropic bladed crystals around masses of galena and sphalerite (Fig. 4). The fact that it is replaced only by fluorite and late calcite favors, but does not prove, that this mineral is one of the latest of the sulfide sequence. In some specimens barite II replaces, in others it is replaced by marcasite, with little evidence of contemporaneity in either case. Since these specimens are from different and widely separated parts of the mineral district, it is assumed that the paragenetic sequence must have varied to some extent between the various areas.

Barite.—Barite occurs in two generations. Barite I, one of the early gangue minerals of the first sulfide phase of the mineralization is in tabular plates, now, for the most part, very badly corroded and replaced by all the

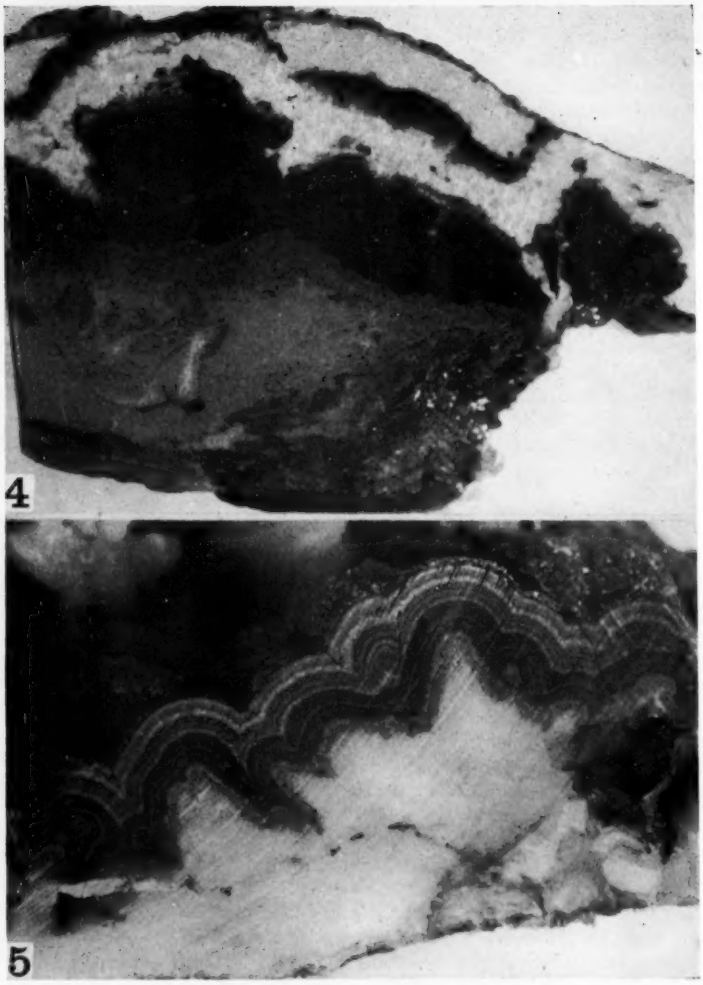


FIG. 4. Layered ore. Base is fine-grained limestone with disseminated sphalerite increasing toward contact with later galena surrounded by marcasite. Late calcite has replaced some galena and marcasite and blende (dark bands) completed the deposition. Bleiberg. × 1.

FIG. 5. Schalenblende (banded wurtzite) surrounding slightly corroded scalenohedra of Calcite II. Outer shell of pyrite with tiny scalenohedra of calcite. Bleiberg. × 1.

later minerals. It is distinguished by the fact that in several places it has been replaced by the yellow sphalerite of the early sulfide phase, a relationship which would be impossible if the barite were later.

Barite II occurs as sheaves and masses of large bladed crystals, up to 1 cm long, which show sharply defined replacement relations toward the minerals of Phases I through IV and the orange wurtzite and early schalenblende of Phase V (see Fig. 6 a).

Zinc Sulfides.—Three forms of zinc sulfide occur in the deposits of the Bleiberg-Kreuth area. The earliest form, crystalline granular yellow sphalerite, which disseminated in the limestone and throughout the zincy ores of the district, is a product of the first sulfide phase of the mineralization.

The remainder of the blende was deposited in the form of wurtzite and schalenblende. Wurtzite forms anisotropic orange rims around the earlier yellow sphalerite crystals (Fig. 6 b). Wurtzite in this form is clearly a product of the second sulfide phase as it replaces galena, the last sulfide deposited in the first sulfide phase.

Schalenblende takes on two forms that are closely allied and may be considered best as separated parts of the same occurrence. To the earlier form, which is brownish to reddish-brown in color, wurtzitic (anisotropic) in character, and replaces the minerals of the previous phases, the name "botryoidal blend" is here applied. This blend replaces galena and is in turn replaced by later barite and marcasite. In the areas where some tectonic movement has taken place, this blend has been broken and recemented by anhydrite, fluorite, and the last generation of calcite.

The true schalenblende is a later form. It encrusts the dog-tooth spar of the second calcite generation and gives the impression of having been formed as a colloidal mass. The color of this mineral is varied in the several layers in which it is formed, but is always brown or yellowish-brown. It has a marked anisotropism. In one particularly conspicuous case the schalenblende has a layer of pyrite crystals covering the smooth curves of the last layer of blend and this, in turn, has a covering of scalenohedral calcite crystals (Fig. 5). This type of texture is clear evidence of formation in an open cavity.

Galena.—Galena occurs as large crystals, most of which have the form of cubes modified by octahedrons, and as veinlets and small masses that replace the early yellow blend and the early gangue minerals. It is itself replaced by many of the later minerals in the sequence, especially botryoidal blend, which forms cockades around the large crystals, with some replacement along the edges and cleavages. Some galena occurs as veinlets which have rounded outlines, suggesting that lines of crystals have been replaced and the "veinlets" are really remnants of these crystals.

In most of the Bleiberg ores the galena shows some shearing as the result of the late tectonic movements. The curved cleavages thus formed are often clearly visible megascopically.

Fluorite.—In most parts of the deposit fluorite is a minor gangue mineral, but in the Bellegarde ore body (in the central part of the district, just northwest of Bleiberg) fluorite is almost the only gangue mineral of any importance. In other areas fluorite is sparingly disseminated in small subhedral

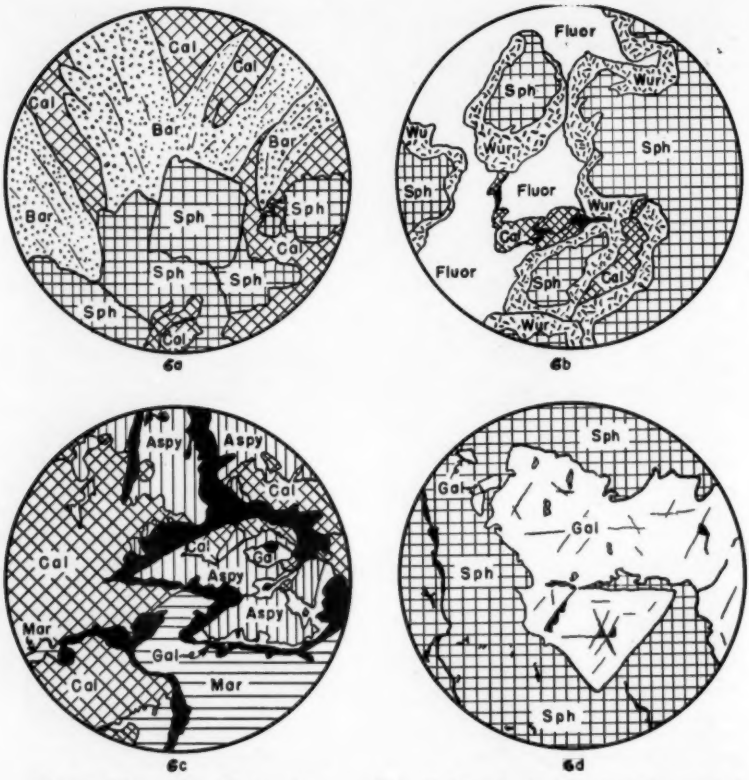


FIG. 6. Camera lucida drawings. *a*. Sheaf of late barite (Barite II) on sphalerite. Bleiberg. × 15. *b*. Anisotropic rims of wurtzite around isotropic sphalerite. Gangue is fluorite and calcite. Cross nicols. Bleiberg. × 85. *c*. Early (?) arsenopyrite surrounded and partially replaced by marcasite, galena, sphalerite, and calcite. Reflected light. Mezica. × 170. *d*. Late zinc sulfide replacing galena. Reflected light. Raibl. × 25.

masses and cubes, most commonly in ores close to the shale contact. Fluorite is considered to be late because it replaces all of the ore minerals.

Anhydrite.—Anhydrite is disseminated through most of the ore deposits in the district in the form of isolated tabular crystals. However, in the Franz-Joseph area in the eastern part of the district, and in a few other small areas where late tectonic disturbance of the ores has taken place, massive bluish anhydrite cements the breccia fragments. This mineral is considered to be primary in origin on the basis of its wide dissemination in other parts of the deposit and its perfection of crystal shape.

Mezica.

The ore deposition in the Mezica area is of the epithermal type. Mineralization is considered to have taken place in three phases which may or may not have been continuous. There is no evidence of discontinuity other than the change in mineral types. The first phase was dolomitization and baritization; the second, sulfide deposition; the third, a second deposition of barite and carbonate with minor amounts of fluorite. The mineralizing solutions were probably weakly acid as evidenced by the deposition of marcasite and wurtzite, which are believed to occur as primary minerals only under conditions of low pH. The ore deposits were then oxidized where near or at the surface.

Carbonates.—Dolomite occurs in two generations. Dolomite I is the earliest gangue mineral. It replaces the Wetterstein limestone both as a grain-for-grain replacement, retaining the original texture of the limestone, but segregating much of the bitumen present into the areas around the grain boundaries, and as larger crystals than those of the original fine-textured limestone, in the form of veinlets (Fig. 7).

Dolomite II is the last mineral deposited. It replaces all the other minerals including sulfides, with the exception of the oxidation products. In thin sections, it is easily seen that dolomite II has either replaced dolomite I almost completely or at least peripherally, the inhomogeneous crystals thus formed having a center of dolomite I. Some calcite also occurs with the late dolomite and in similar relations to the earlier minerals.

Barite.—Barite also occurs in both early and late phases of mineralization. Barite I was apparently deposited as part of the early phase of alteration, later than dolomite I or with slight overlap. The relations are partially obscured by dolomite II. Barite II shows definite replacement relations with dolomite I and the sulfides and is itself replaced only by fluorite and dolomite II. Both generations of barite occur as bladed crystals, isolated or in sheaf-like masses.

Arsenopyrite.—Arsenopyrite has been observed in only one section from the Mezica area (Fig. 6 c). In this section it is the earliest sulfide, occurring both in large masses and diamond-shaped crystals. It shows replacement by all other sulfides and late gangue minerals. Relations to the earlier gangue minerals could not be determined.

Marcasite.—Marcasite is the earliest common sulfide. It occurs as incrustations and disseminated crystals and is commonly replaced by the other sulfides and the late gangue minerals. Some of the disseminated crystals show very weak or no anisotropism and may have partially or wholly inverted to pyrite. This is evidenced by the presence of some zoned crystals in which pyrite and marcasite alternate. There is also a minor late generation of marcasite (and/or pyrite) which occurs as disseminated crystals and incrustations after the deposition of galena. Most of this material is isotropic, but as the conditions of mineralization were probably acidic, it may have been deposited as marcasite and later inverted to pyrite.

Zinc Sulfides.—Zinc sulfide occurs in several colors as both sphalerite and wurtzite. It is assumed that all zinc sulfide was deposited as wurtzite and has inverted to the more stable form with the passage of time. This conclusion is

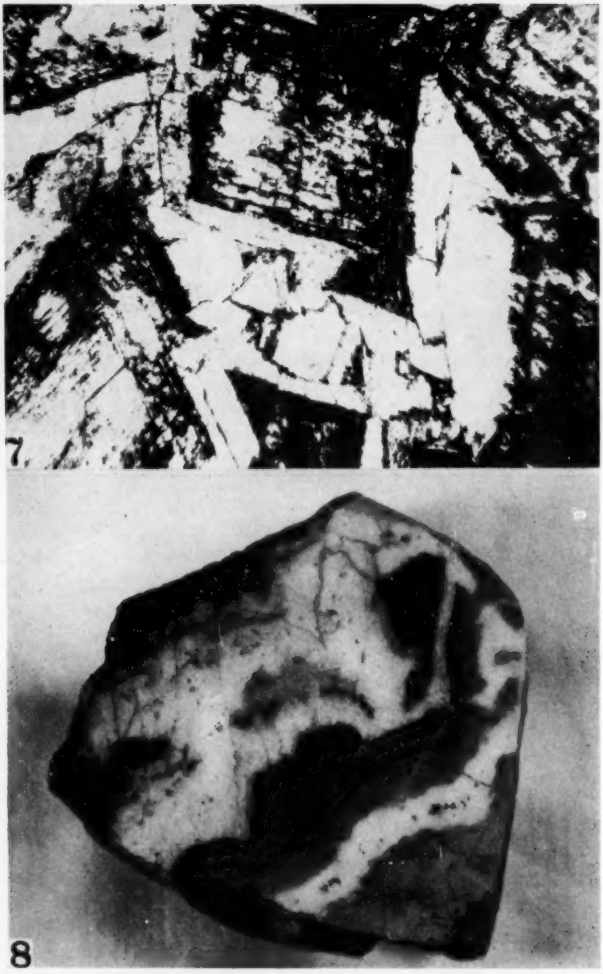


FIG. 7. Inclusions of bitumen show the shape of original calcite crystals which were replaced internally and surrounded from without by epigenetic carbonate. Mezica. × 35.

FIG. 8. One side of a "vein." Original limestone (lower right) is traversed by a vein of late calcite. Galena (black crystals) was replaced by botryoidal blend. Late calcite replaced the sulfides in some places. Note brecciation. Mezica. × 1.

derived from the fact that red zinc sulfide (wurtzite) is found replacing marcasite and is replaced, or at least succeeded by a later generation of yellow zinc sulfide (sphalerite). Apparently either (1) conditions of pH and/or temperature changed to such an extent as to allow the deposition of sphalerite after deposition of wurtzite or (2) some wurtzite has inverted to sphalerite. Ehrenberg (5) has shown that wurtzite inverts to sphalerite very slowly or not at all when over 5 percent of iron is present in the mineral, and that even a small amount of iron will inhibit this inversion to a large degree. As anticipated from that explanation, in the ores here described the more highly colored, iron-bearing form of zinc sulfide occurs as wurtzite and the least colored, pale, translucent, yellow form, presumably not iron-bearing, occurs as sphalerite.

Galena.—Galena occurs as large euhedral crystals (Fig. 8) and in veinlets of all sizes which were deposited after deposition of zinc sulfide had been completed. This is clearly shown by the fact that although galena is replaced by late iron sulfide and gangue minerals, it is in no case replaced by zinc sulfide, but rather often itself replaces sphalerite or wurtzite in veinlets. It also replaces all the other early minerals similarly. Finally, it also occurs as large crystals in dolomite. Some "steel galena"—a highly sheared form of this mineral—is also present. It is related in its origin to post-ore movement, probably along pre-existing faults in the ore zone.

Fluorite.—Fluorite occurs in minor amounts as rare, generally small crystals, which fill in between and to some extent replace the sulfides and gangue minerals.

Secondary Minerals.—Gypsum appeared in veinlets in the specimens showing incipient alteration. Its relation to the other minerals is not clearly established. It appears to be the result of secondary oxidation.

Only two other secondary minerals, cerussite and covellite, have been observed. In the literature examined, no mention was made of the presence of covellite in the Mezica area. This mineral occurs as finely crystalline masses replacing zinc sulfide and gangue minerals. It probably has its origin in very minor chalcopyrite which formed a solid solution in the zinc sulfide, a relation which is often found in lead-zinc ores. No chalcopyrite has been observed in the course of microscopic examination of the ores, however.

Other secondary minerals mentioned by Granigg (10, pp. 188–190) are smithsonite, hydrozincite, wulfenite, anglesite, leadhillite, plumbocalcite, greenockite, and limonite. Small amounts of quartz of uncertain relation to the other minerals also occur, apparently as part of the mineralization, as it shows a replacement relation to the Wetterstein limestone. However, no quartz was observed in the course of this study.

Cave di Predil (Raibl).

The ore deposits at Cave di Predil are of the epithermal type. The mineralization occurred in several phases with some apparent discontinuity in deposition. The first phase was dolomitization. The second phase introduced marcasite, followed by a generation of black crystalline zinc sulfide,

sparsely distributed, and of the more common yellow crystalline and scaley zinc sulfide. This was succeeded by a generation of galena, replaced by and in part contemporaneous with a botryoidal zinc sulfide having bands of bright red, red- to orange-brown, and violet-gray. Minor replacement of this zinc sulfide by white, finely crystalline calcite then took place; locally this calcite shows almost oolitic texture. The galena which accompanied the zinc sulfide is minor. At this juncture the ores were brecciated by contemporaneous tectonic movement. Next, a light yellowish-gray generation of zinc sulfide was introduced. In many cases this replaced the breccia fragments peripherally. It was accompanied by late marcasite deposited as incrustations on the earlier sulfides and also as crystals in dolomite. The last phase was the introduction of barite and minor fluorite with further later dolomitization. The late dolomite cements the brecciated ores.

Carbonates.—Dolomite appears in two major generations, early and late. The early generation permeated the original limestone in the form of veinlets and, to a larger extent, as replacements. In many cases it is distinguishable only with some difficulty, even with the metallographic microscope, but in some cases small remnant crystals of dolomite can be found as inclusions in galena and zinc sulfide. In thin section the distinction is easily made as early dolomite shows inclusions of bitumen, whereas the replacing later dolomite is peripheral to the earlier crystals and shows no inclusions. The late generation, besides forming veinlets of white crystals up to 2 mm in diameter that transect the entire previous sequence of earlier minerals, also constitutes the matrix of the brecciated ores (Fig. 12) in the form of large crystals up to 1 cm in diameter.

Minor fine-textured calcite occurs in association with red and violet-gray zinc sulfide and to a lesser extent with the earlier yellow zinc sulfide as replacements across the banded structure, and as tiny round globules resembling oolites. This calcite appears to be clearly earlier than the late grayish-yellow zinc sulfide and the late dolomite, as it shows the brecciation that affected the ores before the deposition of the grayish-yellow blend and late dolomite.

Marcasite.—Marcasite occurs in two generations. The early generation is the first sulfide present, with the possible exception of arsenopyrite. Arsenopyrite was not observed during the course of the studies here presented but it has been reported in minor amounts by Tornquist (20, p. 165). The early marcasite occurs as botryoidal masses of large crystals, commonly bladed, which exhibit strong blue and greenish-yellow anisotropism. This is replaced by all later minerals, but especially by bands of red zinc sulfide along the interfaces between the earlier marcasite bands.

The late generation of marcasite occurs in two forms: (1) as incrustations on galena, yellow zinc sulfide, and limestone breccia fragments (Fig. 11), and (2) in irregularly shaped, rounded, zoned crystals. Both of these kinds of marcasite show very poor anisotropism, which may indicate partial inversion to pyrite. The late marcasite is in all cases replaced by late dolomite.

Zinc Sulfides.—Zinc sulfide occurs in several generations of different colors. The earliest generation is in pale yellow to orange-yellow finely crystalline disseminated platelets and is accompanied by a slightly later black form

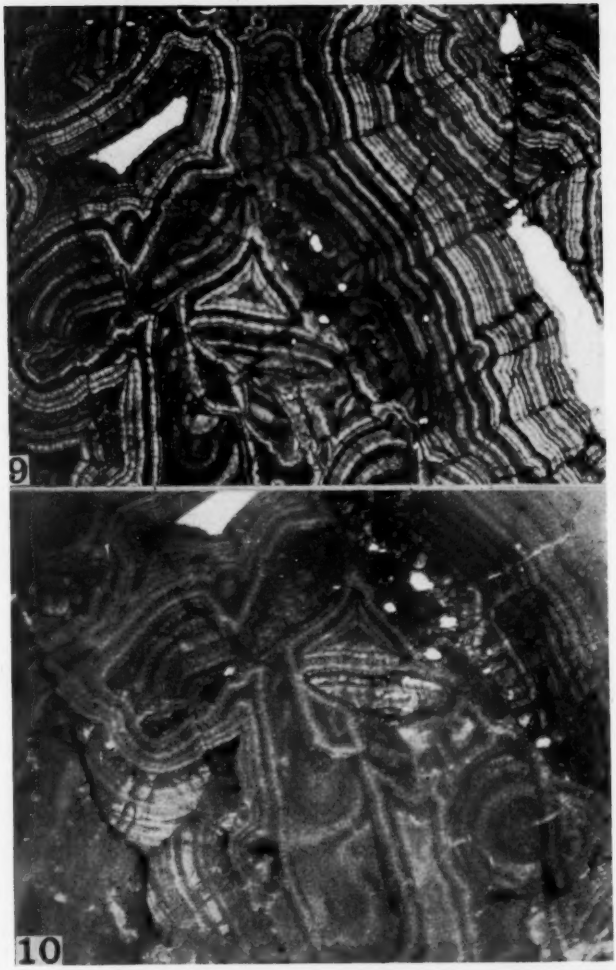


FIG. 9. Schalenblende (botryoidal wurtzite). Ordinary light. Raibl. × 17.
FIG. 10. Schalenblende. Cross nicols. Note the anisotropism showing the wurtzitic nature of the zinc sulfide. Compare with Figure 9. Raibl. × 17.

as crystals up to 2 mm in diameter. Both of these kinds of zinc sulfide show replacement by botryoidal deep red to reddish- or orange-brown and pale violet-gray zinc sulfide. The botryoidal nature of this zinc sulfide is clearly demonstrated in Figures 9 and 12. Galena was apparently deposited both

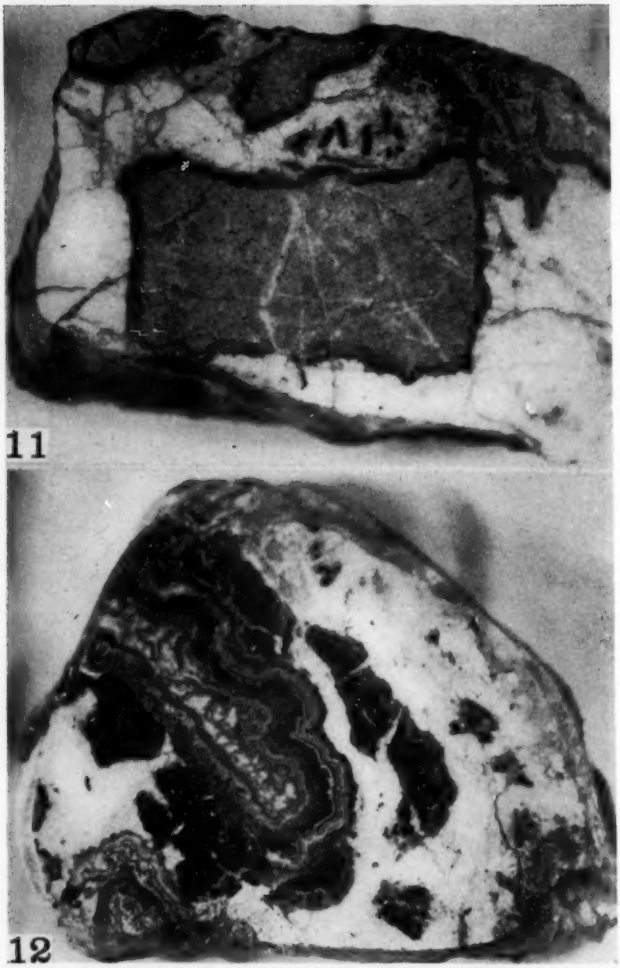


FIG. 11. Pieces of brecciated limestone (Wettersteinkalk) surrounded by early marcasite and recemented by later carbonate. Raibl. × 1.

FIG. 12. Botryoidal blend and galena with carbonate and late barite (upper left, sheaves). Note the brecciation of the sulfides and recementation by carbonate. Raibl. × 1.

previous to and contemporaneously with the later generation of zinc sulfide, but it is definitely later than both the yellow and black forms, which it replaces. The red zinc sulfide shows replacement of the yellow plates and forms cockades around the black zinc sulfide and the galena. In some places these bands of late zinc sulfide appear cut off by the galena crystal which they encircle in an adjacent part of the periphery of the crystal, a relation which results from the bands growing against the face of the galena mass. A later generation of yellowish-gray crystalline zinc sulfide appeared after the brecciation took place as it can be demonstrated to have replaced both the early red zinc sulfide and the marcasite around the edges of the breccia fragments. This red zinc sulfide is always closely associated with marcasite and the wine red form occurs only as incrustations on or replacement bands along the planes of banding of early marcasite. Its red color is attributed to its high iron content, derived from the resorbed marcasite. This zinc sulfide is clearly wurtzite, being anisotropic (Figs. 9 and 10). In fact, most of the zinc sulfide, with the possible exception of the late yellowish-gray generation, is believed to have been deposited as wurtzite, whether now sphalerite or not. The evidence for this is the ubiquitous nature of marcasite and red zinc sulfide (wurtzite); these both could only have been deposited under conditions of low pH. As explained in discussing mineralization at Mezica, the iron-rich red zinc sulfide would invert very slowly or not at all. Thus it is always found as wurtzite, while the other botryoidal forms are only slightly wurtzitic and the crystalline forms are sphalerite. The red zinc sulfide also shows rather close association with minor late calcite, which cross-cuts it and locally forms narrow units in the banded sequence described.

Di Colbertado (5, pp. 284–285), in his description of the Raibl deposits indicates that there is a rough zoning with respect to the forms of blende. The red blende occurs mostly in the northern part of the deposit. The botryoidal blende occurs in its greatest concentration in the central part of the deposit. The crystalline forms of blende show their greatest development in the southern part of the mineralized area. In no case does Di Colbertado indicate that the division is a strict one, however; it must be assumed that all forms are found throughout the deposit in varying proportions.

Galena.—Galena appears to have been fairly early in the sequence. The most prominent form is in large cubes and octahedrons up to 3 cm in diameter (Fig. 12). These crystals are surrounded by red to violet-gray zinc sulfides and apparently replaced the earlier generations of zinc sulfide (Fig. 6 d). Galena also forms lines of small crystals which appear to be crusted vein fillings. It occurs in lesser amounts in "mutual" contacts, suggesting contemporaneity in deposition with the red zinc sulfide; in such cases it forms fine discontinuous bands between the bands of zinc sulfide and also forms tiny veinlets cutting the earlier banding of the zinc mineral. Finally, some galena is found as fine disseminations in early dolomite.

Barite.—Barite occurs here only in a late generation as white needles with characteristic sheaf-like arrangement. These typically replace the early sulfides and other early gangue minerals.

Fluorite.—Fluorite, identifiable only under the microscope, appears in small amounts as fillings in interstices between sulfides and as small blebs in dolomite. It is distinguished by its dark gray color, smooth surface, and in rare instances, by evidences of octahedral cleavage. This mineral was deposited later than all the sulfides.

Other Minerals.—Di Colbertado (5, p. 286) also mentions the occurrence of pyrite, pyrrhotite, chalcopyrite, and cinnabar in quantities of secondary importance or as rare minerals. The presence of pyrrhotite is noteworthy and surprising.

Oxidized Ores.—The oxidized products are said to be calamine, hydrozincite, cerussite, limonite, and a blue copper stain.

COMPARISON OF THE DEPOSITS.

From the comparison of the structure and mineralization (Table 2) the following conclusion is drawn:

The ore deposits appear to be of similar origin but the mineralizing solutions varied somewhat in composition and acidity. The largest similarity is found between the deposits of Raibl and Bleiberg. Their close proximity to each other is a partial confirmation of this thesis. The mineralization at Mezica is probably related to another similar intrusive. On the basis of these and structural and control features, it is believed that there is enough similarity in the sequences of mineralization and mineral suites to imply that there is a definite relationship among these three deposits.

NATURE OF THE MINERALIZING SOLUTIONS.

For many years economic geologists have been divided over the problem of whether hydrothermal solutions (or their equivalent gaseous phases) were acid or alkaline in nature. Basically, of course, some of the argument depends upon the definitions used for the terms acid and basic. Some have maintained that any solution that does not contain free strong acid is alkaline in nature, while others have defined the terms on pH. This has been brought out by Fenner (7).

The definitions of chemistry state that if pH is above 7 (i.e., if OH_3^+ concentration is less than 10^{-7}), the solution is alkaline; if pH is below 7, the solution is acid. Neutrality is defined by the pH value 7. These are the definitions used for the terms in this paper. It may be assumed that a condition near neutrality is found in solutions with pH between 6.5 and 7.5. However, it should be noted that any solution with pH other than 7 will tend to have the characteristics of an acidic or basic solution, according to the side of 7 on which the pH lies. Therefore, care should be exercised in using the term neutrality, especially since under conditions of heat and pressure such as are thought to have prevailed during the formation of mineral deposits, the chemical reactivities, solubilities, and other properties of solutions and compounds may increase; similarly, the effect of pH, which depends upon heat and pressure, may become correspondingly greater.

Since the assertion that ore deposition takes place from "alkaline" solutions has been made again and again in the literature (11, 18) while others maintain that acidic solutions were the media of mineralization in many cases (7, 13, 8), the author wishes to discuss the problem of the formation of the three ore deposits here under study from both points of view.

TABLE 2.

COMPARISON OF STRUCTURE AND MINERALIZATION.

	Mezica	Bleiberg	Raibl
1. Genesis time	Tertiary	Miocene-Pliocene	Oligocene-Miocene
2. Source	Acid intrusive	Basic? probably acid intrusive	Acid intrusive
3. Structure	Anticlines, tear faults, bedding plane movement	Syncline, large and small tears, bedding plane movement	Large tears, bedding plane movement
4. Control	Shale cover	Shale cover	Shale cover
5. Ore horizon	Wetterstein Ls.	Wetterstein Ls.	Wetterstein Ls.
6. Solutions	Moderately acid	Late highly acid, early mildly acid or neutral	Moderately to strongly acid
7. ZnS	2 forms, no schalenblende	3 forms, late schalenblende	4 forms, early sphalerite, later schalenblende
8. Galena	Before ZnS	After early ZnS, before schalenblende	After early ZnS partly contemporaneous with other forms of ZnS
9. Gangue			
a. Carbonates	Dolomite and minor calcite	Mostly calcite	Dolomite and minor calcite
b. FeS_2	Marcasite early, marcasite and/or pyrite late	Marcasite late, pyrite early(?) and late	Marcasite early and late
c. Barite	Early and late	Early and late	Late only
d. Fluorite	Minor	Important	Minor
e. Anhydrite	Minor	Important	Not noted

On the alkaline side, Smith (19) has shown that zinc and lead sulfides are soluble to a *limited extent* in solutions of sodium hydrogen sulfide and sodium polysulfide at high temperatures and that from such solutions sphalerite crystallizes out before galena on cooling. The experiments were carried out by heating the reagents and sulfur with zinc chloride and lead chloride in a graphite-lined steel bomb to a temperature of 425° C and slowly cooling them. The general order of events in the precipitation was as follows:

1. Crystallization of sphalerite (Octahedrons or cube-octahedrons).
2. Crystallization of galena (cubes).
3. Sphalerite was attacked by the solution which removed some zinc sulfide and later deposited it as small crystals, as amorphous zinc sulfide, or as hexagonal wurtzite.
4. Galena was attacked to a lesser degree and the dissolved lead sulfide deposited later as microcrystalline galena.

Colloidal dispersion was postulated to be the cause of "re-solution." Smith concluded that the fact that solution did take place and that the generally accepted paragenetic order was followed showed that this might be the method of ore deposition. This hypothesis may be examined with other evidences, especially with respect to the ore deposits of Bleiberg-Kreuth, Mezica, and Cave di Predil.

(1) It has yet to be demonstrated that such solutions may transport large amounts of zinc and lead sulfides at lower temperatures than 425° C. This scarcely fits the picture of mesothermal or probably epithermal or telethermal deposition (300° C or less) that is found in the mineralized areas in question. Also, Garrels (8) has pointed out that not only are alkaline sulfide solutions the media in which common metallic sulfides are least soluble (with the possible exception of zinc and the Group 2b metals), though colloidal dispersions may be obtained, but the concentrations of hydroxyl and sulfide ions required for solubility of any significant amount would have to be fairly large (0.3–0.4 molal). He concludes, "Therefore, since some metals do not form true solutions in an alkaline medium, and those that do require high sulfide ion concentrations, it seems that dilute alkaline solutions are a very poor medium for ore transport." The author is in agreement with this idea.

(2) It seems improbable that alkaline solutions could cause any significant solution of limestone or even enough solution to allow replacement. Of course, heat may cause decomposition of limestones. It has been argued that acid solutions should cause excess solution of the limestone, thus leaving cavities in the deposit. Such cavities are not typical of replacement deposits. Also, carbonates are not deposited from acid solutions. However, it is entirely possible that solutions with pH in the range between 6.5 and 7.0 could cause slow enough solution to prevent formation of large cavities and only enough to allow replacement. This is because neutralization of the solution when the limestone is dissolved causes simultaneous deposition of the sulfides to replace the removed limestone. Carbonate deposition would probably occur on reaction and neutralization.

(3) The presence of radicles of strong acids, such as the sulfate and fluoride radicles, in the barite, fluorite, and anhydrite commonly present in the gangue of these and many other deposits indicates the presence of solutions which would have a slightly acid reaction upon hydrolysis, even without the presence of free acid. Sodium sulfide solutions are unstable when pH is below 7. It may also be noted that deposition from alkaline sulfide solutions would probably cause precipitation of free sulfur. No free sulfur has been found in these deposits.

(4) Despite some similarities between the types of deposition in alkaline solutions and those of ore deposits, there are some discrepancies, notably the reversal of depositional order between lead and zinc sulfides in the later stages of mineralization in these deposits.

(5) The presence of wurtzite, and especially marcasite, two mineral forms which, except at very high temperatures, are stable only in acid solutions indicates that the solutions were probably of pH lower than 7.

On the acid side, Kristofferson (14) has shown that not only are lead and zinc able to be transported as volatile chlorides in the presence of hydrogen sulfide and hydrogen chloride above 300° C, but also that it is possible that such transportation may occur in solutions at lower temperature. Deposition would take place upon neutralization of the acid. In support of this, Garrels (9) has shown that transportation may take place in solution by the formation of complex chloride ions, and that in such solutions deposition of the type found in the deposits at Raibl and Bleiberg-Kreuth (i.e., with reversed order of deposition of lead sulfide and zinc sulfide) may also occur. It is not necessary that the pH in these solutions be much lower than 6, if even that low. Such soluble chloride ions might easily be removed with the removal of depositing waters. That ore deposition of this type occurs from gaseous effusions containing hydrogen chloride and hydrogen sulfide has been demonstrated by Allen and Zies in their studies in the Valley of Ten Thousand Smokes (2). Lead and zinc sulfides were deposited there from fumarolic emanations of this type. Newhouse (16) has shown that inclusions in galena and sphalerite in deposits of the "Mississippi Valley" type throughout the world contain calcium and sodium chlorides. Thus, the probable presence of the chloride ion in such deposits as well as the acid nature of the gaseous emanations that deposited similar minerals in the Valley of Ten Thousand Smokes has been established.

In the case of acid solutions, most of the above objections to alkaline solutions are overcome. It may also be demonstrated on chemical grounds that the later phases of the ore deposition, in which apparently colloidal deposition occurs (formation of late schalenblende) at Bleiberg is the result of acid solutions.

Figure 13 shows that wurtzite and amorphous zinc sulfide form at low temperatures in acid environments. The wurtzitic nature and colloidally deposited appearance of this schalenblende may thus be explained. That the solutions could not have been strongly acid is shown by the extremely small amounts of resorption of the calcite scalenohedra on which the schalenblende has been deposited. Late pyrite, also formed at about this time, may indicate that neutralization of the solutions had proceeded to a very high degree of completion, or that at this stage, the solutions may even have been slightly on the alkaline side. This pyrite is slightly later than the schalenblende.

Graton (11) has indicated that the original solutions separated from the magma were necessarily basic. This may well be, as Butler (4) has shown that oxidation may cause the formation of sulfuric acid and deposition of primary sulfate minerals from sulfide ions. However, as Garrels (9) has suggested, it is not necessarily so that, because solutions are rich in ions of strong

alkalies such as sodium and potassium, they must necessarily be alkaline in nature. These ions are capable of existence with halogens or sulfate ions in acid solutions. Thus the solutions need not be basic (i.e., of high pH) at all.

In conclusion, on the basis of the evidences here presented and the relations of the ores, it must be assumed that the solutions which formed these deposits,

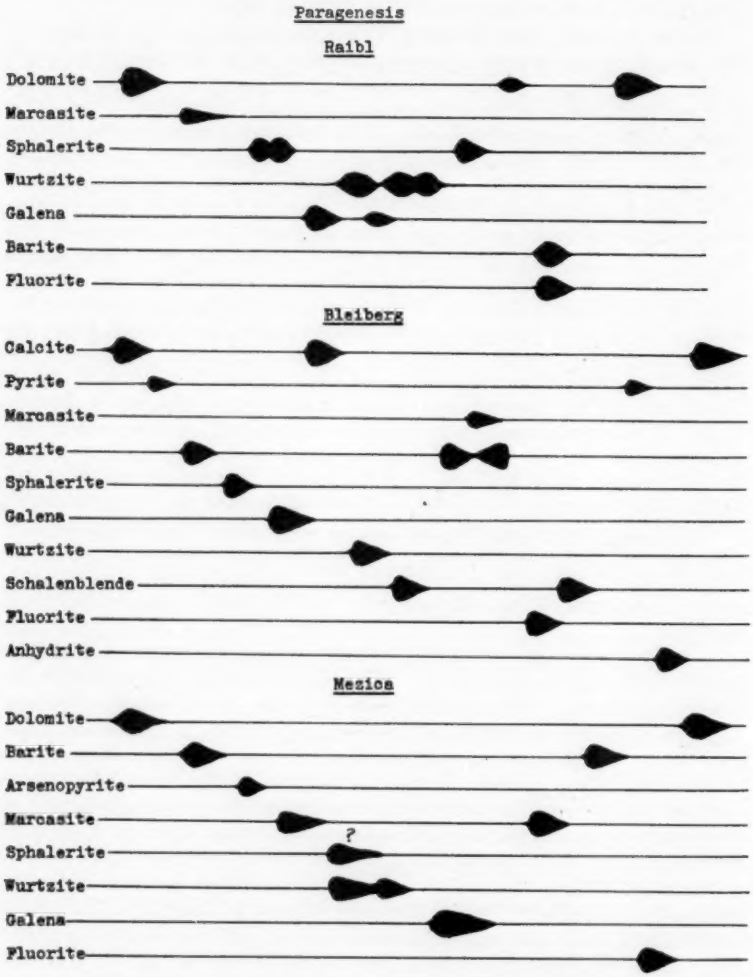
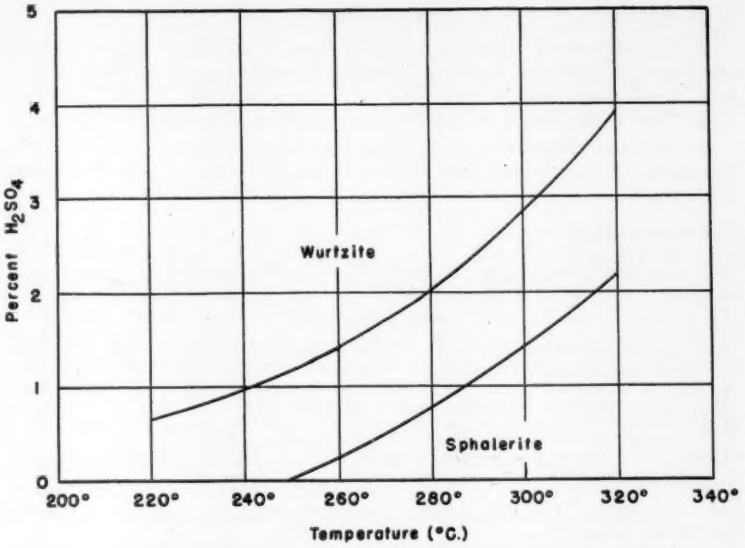


FIG. 13. Paragenetic relations at Raibl, Bleiberg, and Mezica.



Fields of Precipitation of Sphalerite and Wurtzite

Percent H_2SO_4

Temp.(°C.)	1.0	2.5	4.0	5.0	7.5	10.0
250	S & W	W & A		W & A		
300	No W Little A	No W	70% W & A	5% W	90% W	All W
350		70% W		30% W		80% W

S = Sphalerite W = Wurtzite A = Amorphous zinc sulfide

FIG. 14. Fields of precipitation of sphalerite and wurtzite (after Allen and Crenshaw, and Mellor).

regardless of their past history, were acidic in nature during the time of formation of these mineral deposits. This means only that the solutions had a pH less than 7, regardless of their original composition of strong or weak acid anions or basic cations.

With regard to other deposits, it is difficult to make a statement covering all types, but in any event, the author is convinced on the basis of the above arguments that lead-zinc deposits of the "Mississippi Valley" type, at least, were formed from solutions whose pH was less than 7.

CONCLUSIONS.

1. On the basis of age relations of the deposits, structural and control features, and the similarity in the sequences of mineralization and mineral suites, there is a definite relationship among these three deposits.

2. The ore deposition in all three districts has been from acid solutions.

3. The ore deposition in similar deposits (Mississippi Valley type) throughout the world has probably been from acid solutions (solutions whose pH is less than 7).

DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
NEW YORK CITY,
April 12, 1951.

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GEOLOGICAL INVESTIGATIONS AND GEOCHEMICAL PROSPECTING EXPERIMENT AT JOHNSON, ARIZONA.[1]

JOHN R. COOPER AND LYMAN C. HUFF.

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ABSTRACT.

Deposits of copper and zinc at Johnson, Arizona, occur in metamorphosed Paleozoic limestone near a quartz monzonite stock probably of late Cretaceous or early Tertiary age. The metallic mineralization was preceded by a stage of thermal metamorphism during which pure carbonate beds were recrystallized and impure carbonate beds were altered to garnet, diopside, and other contact-metamorphic silicates. Silicate formation, which involved loss of carbon dioxide, was accompanied by shrinkage that reached a maximum of 30 percent. In the following metallic mineralization, the metamorphic rock was replaced by copper and zinc sulfides associated with some chlorite and other relatively low temperature gangue minerals. Nearly all the ore occurs as tabular masses and chimneys in particular beds in the Abrigo formation of Cambrian age.

The recently discovered Moore ore body is a lenticular mass in the Abrigo formation about 400 feet below the present surface. Faulted and fractured limestone and dolomite beds of the Escabrosa limestone (Mississippian) crop out above the ore body. Local copper stains, which are abundant in the district, and a greater-than-average amount of faulting are somewhat meager geological evidence for the presence of ore.

To determine if there was any geochemical evidence for the proximity of ore, outcrops of the Escabrosa limestone and part of the underlying

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Martin formation (Devonian), the fault zones, and soils were sampled both over the ore and in the adjoining area, and the samples were analyzed for traces of the ore metals.

The ore-metal content varies widely and is determined in part by stratigraphy and structure. Large areas abnormally high in ore metal are indicated by samples from the fault zones. Composite chip samples of the rock between the faults show small high areas within the high areas indicated by the fault-zone samples. One of the chip-sample anomalies is over the Moore ore body but displaced somewhat to one side of the center of the body. Two other anomalies are over unexplored ground some distance from the ore body. Soil samples collected on low ridges, where contamination is unlikely, show the same general anomalies as the rock samples.

A genetic relationship between the Moore ore body and the nearby geochemical anomaly is suggested by its proximity and by the presence in the anomaly area of fault zones which carry concentrations of ore metal and project toward the ore. Diamond drilling and further geochemical studies are suggested as possible means of checking the inferred relationship. At present, geochemical studies give promise of becoming a valuable adjunct of geology in prospecting the Johnson district and similar areas elsewhere.

INTRODUCTION.

THE time-honored profession of prospecting has undergone many changes through the years. At one time an individual with no more than primitive equipment, a smattering of knowledge concerning ore deposits, and fortitude had a good chance of finding valuable ore deposits. Many of the deposits found were easily recognizable from the surface outcrop and were profitable from the grass roots down.

Unfortunately, most of the deposits of this kind have been found and many have been exhausted. Although the needs of industry continue to increase, ore deposits have become more and more difficult to discover. At present, prospecting commonly consists of detailed geological study, expensive drilling or other exploratory development, and possibly geophysical studies, all integrated so that every pertinent scrap of knowledge can be utilized. New discoveries continue but with ever-increasing cost in time and trouble; continual improvement of prospecting methods is a vital necessity.

The use of trace analysis to detect and map natural materials with a higher-than-average content of the ore metals, i.e., geochemical prospecting, offers possibilities of facilitating the discovery of new ore bodies. Most geochemical prospecting in the past has been confined to the analysis of vegetation, soil or other weathering products; i.e., investigations of the supergene dispersal of the ore metal (2, 3, 7).[2] Recently, however, chemical prospecting studies in the mining district at Tintic, Utah, have discovered evidence indicating a hypogene or primary dispersion of ore metals in volcanic rocks overlying the ore bodies (6). It seems highly desirable to investigate primary dispersion in other environments.

This paper presents the results of such an investigation in the Johnson mining district. This district seemed favorable for geochemical study because the geology has been studied in considerable detail; and surface showings of copper

[2] Numbers in parentheses refer to Bibliography at end of paper.

minerals have been found above several deep-lying ore bodies in the district, suggesting that partially spent ore solutions may have leaked almost straight upward.

The Johnson district is in southeastern Arizona, about 55 miles east of Tucson, 45 miles north of Bisbee, and 55 miles southeast of San Manuel. Mining in the district has been carried on intermittently since 1881 and has resulted in a total production of about $10,000,000 in copper and zinc ores. Economically, the deposits are marginal; most of the ore contains from 1½ to 4 percent copper and 2 to 15 percent zinc. The most productive periods were 1914–20 and 1944–49. All mines in the district were inactive between July 1, 1949, and July 1, 1950, because of low metal prices. The largest property owner at present is the Coronado Copper and Zinc Company, which is controlled by the Harvey S. Mudd interests of Los Angeles. This company purchased the most productive mines in 1942 and has subsequently purchased some of the surrounding claims.

A detailed study of the geology of the Johnson area was begun in 1944 by J. R. Cooper of the U. S. Geological Survey. L. C. Huff of the Survey's geochemical prospecting section visited the area on February 4, 1948, and March 23, 1949. Samples of soil and bed rock collected on these occasions and additional samples collected by Mr. Cooper in April 1949 were analyzed for traces of ore metal, with encouraging results. Field work for the systematic geochemical study described in this report was conducted jointly by Messrs. Cooper and Huff between October 12 and November 6, 1949. Mr. Cooper is responsible for the geologic mapping and geologic interpretations and Mr. Huff for the chemical analyses; they are jointly responsible for the sampling and geochemical interpretations.

Acknowledgments are gratefully extended to the Coronado Copper and Zinc Company for permission to make the investigation, for information concerning the ore body obtained by core drilling, and for the use of a house that served as a field laboratory.

PHYSIOGRAPHIC AND GEOLOGIC SETTING.

The Johnson mining district is in the Little Dragoon Mountains, a range about 10 miles long and 6 miles wide in the Basin and Range physiographic province. The deposits are at the base of the main mountain mass. The area of geochemical study, shown in Figures 1 and 2, is a rock pediment of low relief and fairly abundant rock outcrops. It is bounded on the west by foothills and on the east by a typical desert-type alluvial fan.

Within the areas mapped as bedrock in Figure 2, the soil is thin and rocky; it is obviously a product of immature weathering, as it contains many fragments of fresh rock. The Quaternary alluvium and slope wash shown on Figure 2 are poorly stratified and sorted mixtures of silt, sand, and angular pebbles. This surficial material is less than 10 feet thick in most of the area but thickens rapidly along the northeastern margin.

The regional geologic setting is described only briefly here as a detailed description of the area is planned for later publication by the Geological Survey. The area of interest is within a belt of sedimentary and metamorphic rocks that

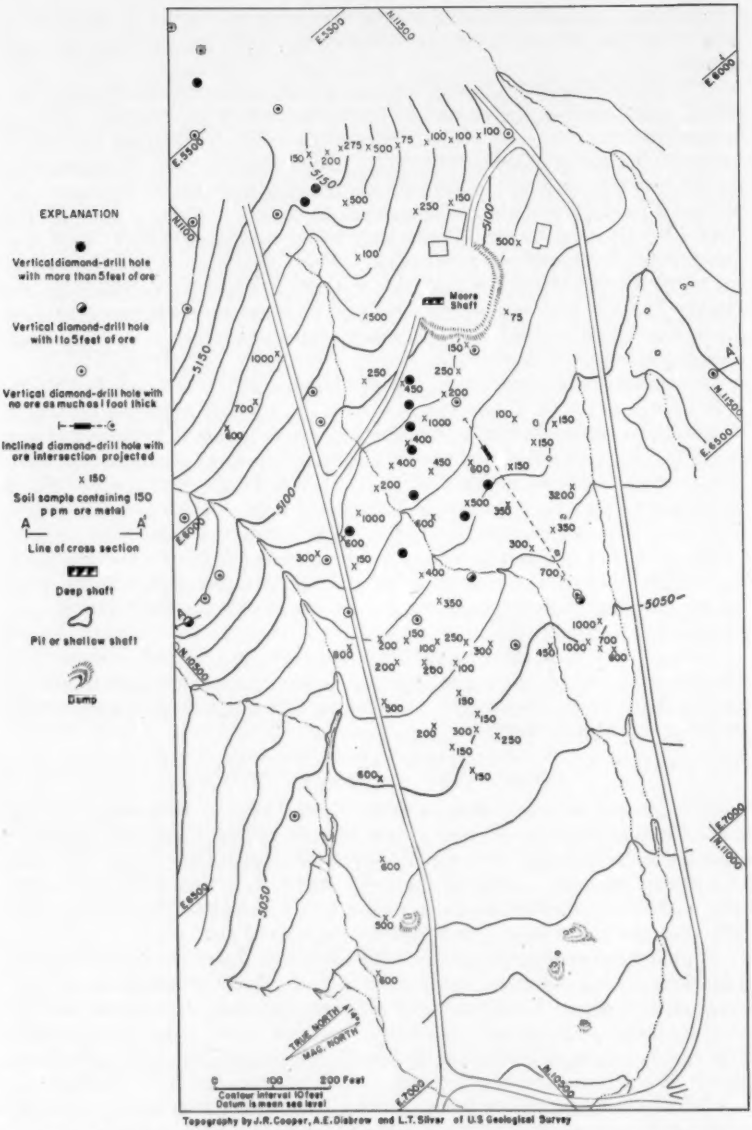

FIG. 1. Topographic map of the Moore ore body area showing diamond-drill holes and geochemical data on soils.

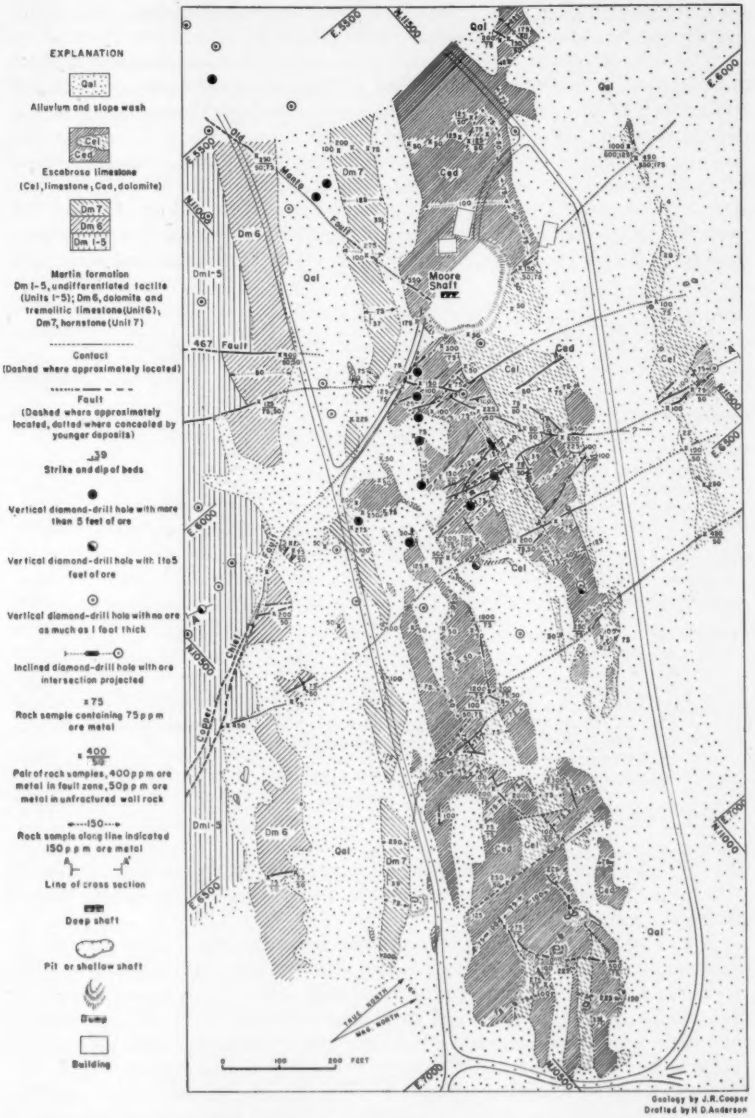

FIG. 2. Geologic map of the Moore ore body area showing diamond-drill holes and geochemical data on bedrock. .

are marginal to a large igneous intrusion, the Texas Canyon stock. The stratigraphic section of this area is summarized in Table 1.

The older Precambrian Pinal schist crops out half a mile southwest of Johnson and consists of highly metamorphosed feldspathic sands, silts, and volcanic rocks intruded by various igneous rocks. The younger Precambrian formations rest on the schist with profound angular unconformity. The Paleozoic rocks are essentially concordant on the younger Precambrian though regional relations indicate a local discordance of several degrees. The rocks exposed near Johnson are of Paleozoic age; they strike northwest and dip 20°–40° NE toward the adjacent basin. The tilting of the Paleozoic formations presumably took place during the Laramide revolution, of late Cretaceous and early Ter-

TABLE 1.

GENERALIZED STRATIGRAPHIC SECTION NEAR JOHNSON, ARIZONA.

	Thickness (feet)
Quaternary and Tertiary: Alluvium	0–550+
Unconformity	
Carboniferous:	
Naco limestone	1,050
Unnamed limestone unit	140
Escabrosa limestone	585
Devonian: Martin formation	240
Disconformity	
Cambrian:	
Abrigo formation	685
Bolsa quartzite	20–335
Unconformity	
Precambrian:	
Younger Precambrian:	
Apache group:	
Dripping Spring quartzite	300
Barnes conglomerate	3–15
(Diabase sills of pre-Bolsa age, 50–150 feet thick, commonly separate the Pioneer shale and the Barnes conglomerate.)	
Pioneer shale	260
Scanlan conglomerate	0–30
Unconformity	
Older Precambrian: Pinal schist	?

tiary time, for Lower Cretaceous sedimentary rocks (Bisbee group) are folded with the older rocks in other parts of the Little Dragoon Mountains and in surrounding areas.

The Texas Canyon stock was intruded after the post-Lower Cretaceous deformation, for it locally transects folded Paleozoic and Mesozoic rocks. The stock is a porphyritic biotite-quartz monzonite with conspicuous phenocrysts of microcline. Dikes of aplite and lamprophyre, both probably differentiates of the quartz monzonite magma, intrude the quartz monzonite and the country rocks. The ore deposits at Johnson are attributed to this intrusive cycle; for reasons presented elsewhere (1, pp. 35–36), the ore deposition is thought to have followed intrusion of the lamprophyre, which is the youngest member of the intrusive sequence.

The exposed portion of the Texas Canyon stock has the shape of a crude oval 7 miles long and 4 miles wide. One end of the oval is in the Precambrian rocks half a mile southwest of Johnson. A subsurface extension of the stock into the Johnson mining district is inferred because (a) the long axis of the intrusive body trends northeast toward the mineralized area; (b) the northeast end of the body has an unusually irregular contact, which may be interpreted as the trace of a roof plunging beneath the surface at a moderate angle; (c) loose blocks of quartz monzonite found at one place near the center of the mining district cannot be explained by transportation from any known outcrop and suggest that an apophysis was once exposed in an area now covered by alluvium; (d) quartz monzonite is exposed along the west side of a low bedrock ridge 2 miles northeast of the mining district; and (e) the alteration of the Paleozoic formations in the mining district is the kind characteristic of igneous contact zones and the alteration is so distributed as to suggest the inferred extension. However, no quartz monzonite has been found in mine workings or borings in the mineralized area.

GEOLOGY OF THE ORE DEPOSITS.

General Features.

The Johnson copper-zinc deposits are pyrometasomatic replacements of favorable limestone beds at or near the intersection of these beds with fractures. More than 95 per cent of the ore has come from beds at the top of the middle member of the Abrigo formation (Table 2). Some ore bodies are tabular deposits in the plane of the beds and are 3 to 20 feet thick and several hundred feet across. The largest deposits are chimneys, more or less oval in cross section with their long and intermediate axes in the plane of the beds. A chimney is known locally as a "manto" if its long axis lies at a large angle to the dip of the beds. The largest ore body mined in the district, the Main Manto at the Republic mine, was 1,500 feet long, 30 to about 100 feet wide, and 15 to 40 feet thick, and had several large extensions of the bedded type.

The rocks of the mining district strike northwest and dip northeast, generally at about 40°. They are cut by three principal sets of faults and fractures: a well-defined set striking N 5°–30° E and dipping 60°–80° SE, called the Northeasters; a less well defined but important set striking about east and dipping 30°–60° S, the Easters; and a relatively inconspicuous set striking N 10°–45° W and dipping more than 65° SW or NE, the Northwesters. Some subsidiary fractures strike essentially parallel to the Easters but dip more than 60° S. With a few exceptions among the Easters and Northwesters, the faults are normal faults. The displacements range from almost nothing to a few tens of feet on most of the faults; they locally exceed 100 feet on several faults, including the Copper Chief fault, a Northwester that crosses the area of the geochemical study (Fig. 2).

Most of the faults are pre-ore, though movements were recurrent during and after the period of ore deposition. That some of the movement was pre-ore is indicated by the fact that faults belonging to each set have localized ore at one place or another in the district. For example, an important ore chimney

was mined a short distance south of the area shown in Figure 2, along the intersection of the 467 fault (Northeaster) with the favorable beds at the top of the middle member of the Abrigo formation. Elsewhere in the district, narrow ore veins cross the beds along both the Easters and Northwesters. The Easters also appear to have been important in localizing mantos, for the two known mantos in the district were both in the favorable beds at the top of the middle member of the Abrigo near and parallel to a major Easter. This relationship can hardly be fortuitous and is thought to indicate that the ore was localized by obscure minor structures associated with the large Easters. At least two periods of fault movement, each followed by the introduction of quartz, are indicated for some Northeasters by brecciated early quartz fillings cut by later unbrecciated fillings. Alternating movement on the various fault sets is indicated at one place in the Republic mine. There, a conspicuous Northeaster that was lined with a 3-foot band of quartz was cut and offset a few feet by an Easter; but later movements reopened the Northeaster across the Easter and this fracture also was filled with quartz. Post-ore faulting is indicated by fragments of ore in the gouge of some of the faults. The "offset" of ore bodies along faults is not a reliable criterion of post-ore faulting in the district because the stratigraphic control of ore deposition was so strong that after the fault movement ceased, the same beds may have been mineralized on the two sides.

The primary ore consists of various proportions of chalcopyrite, sphalerite, bornite and pyrite, a little scheelite, and traces of molybdenite in a gangue of lime-silicates, potash feldspar, calcite, and quartz. The most abundant lime-silicates are garnet, diopside, and epidote; vesuvianite and wollastonite are abundant locally. Within the zone of oxidation, which generally extends to a maximum depth of 50 feet, the ore minerals are chrysocolla, malachite, tenorite, native copper, hemimorphite, and aurichalcite. There is little evidence that copper was leached from the oxidized zone, and almost no evidence that it was redeposited in a zone of secondary enrichment below. Oxidized ores were mined in the early history of the district, but nearly all the ore mined in recent years has been primary ore.

The primary mineralization is divisible into two stages, an earlier metamorphic stage and a later metasomatic stage. The metamorphic stage, which might also be called the thermal or non-additive stage, affected a large area near Johnson presumed to be the roof of the Texas Canyon stock. The metamorphism resulted from increase in temperature and involved the loss of carbon dioxide and the chemical rearrangements of the other constituents of the rock. In general, the mono-mineralic rocks like quartzite, pure limestone, and pure dolomite were recrystallized without the formation of new minerals; whereas rocks like shale and mixed calcareous or dolomitic sediments were profoundly altered mineralogically and texturally. The shales were converted to aphanitic hornstone, the mixed calcareous sediments to granular lime silicate rocks, and the mixed dolomitic sediments to granular lime-magnesia silicate rocks.

The geochemical prospecting study, described later in this report, indicated that the ore-metal content is related to the composition of the host rock, which,

therefore, must be considered in interpreting the geochemical results. A stratigraphic section describing the lithology in the vicinity of the deposits is given in Table 2 and can be used as a basis for interpreting geochemical data and as an aid in deciphering structure. The names of distinctive units are given in parentheses. Some of the units, like the "hornstone marker" at the top of the Martin formation, are everywhere present; others, like the quartzite beds in the Abrigo formation, are only distinguishable locally; a few, like the "lower

TABLE 2.

PARTIAL SECTION IN JOHNSON METAMORPHIC AREA (COMPOSITE).

	Thickness (feet)
Escabrosa limestone, in part:	
Alternating limestone and dolomite units, some with metachert nodules	300+
Dolomite	150
Martin formation:	
Hornstone, light gray, with disseminated pyrite; consists largely of diopside, tremolite, and orthoclase (Dm7 or "hornstone marker")	30
Dolomite, showing some stylolites (Dm6 or "stylolitic dolomite")	85
Limestone, containing some tremolite and serpentine; metageodes are conspicuous on weathered surface (Dm5 or "upper serpentine marker")	10
White tactite, granular; about 75 percent diopside (Dm4)	50
Quartzite containing some diopside (Dm3 or "quartzite marker")	5
Hornstone, light gray; consists largely of diopside, chlorite, and othoclase (Dm2)	8
More or less limy dolomite, generally containing a little chlorite and other silicates (Dm1)	25
Total thickness of Martin formation	213
Abrigo formation:	
Upper member:	
Quartzite containing some diopside (Abrigo unit 10)	3
White tactite, granular, rich in diopside (Abrigo unit 9 in part)	12
Limestone; contains scattered half-inch masses of forsterite or serpentine ("lower serpentine marker") (Abrigo unit 9 in part)	12
White tactite, granular, rich in diopside and orthoclase (Abrigo unit 8 and Abrigo unit 9 in part)	63
Quartzite containing some diopside (Abrigo unit 7)	4
White tactite, granular, rich in diopside and orthoclase (Abrigo unit 6)	24
Middle member:	
Interbedded limestone and hornstone, commonly garnetized and locally containing ore (Abrigo unit 5 or "ore beds")	50
Calcareous sandstone, commonly garnetized (Abrigo unit 4)	26
Limestone with abundant irregular partings of dark hornstone, locally garnetized in part (Abrigo unit 2 and Abrigo unit 3, "crenulated beds")	172
Lower member: Shaly hornstone; includes occasional bands of limestone or garnet tactite (Abrigo unit 1 or "shale marker"), thickness measured outside metamorphic area	300
Total thickness of Abrigo formation	666

serpentine marker," are conspicuous concentrations of a rock type that locally appears in small quantities in other parts of the section.

As shown in the section above, the thicknesses of the Abrigo and Martin formations are somewhat less than the corresponding thicknesses measured outside the metamorphosed area and presented in Table 1. The difference is thought to signify a decrease in volume of the rock through loss of carbon dioxide and through the formation of relatively dense silicates during metamorphism. The thicknesses in the metamorphic area vary directly with the amount

of carbonate remaining in the rock. For some individual members, the thickness of the silicated facies is nearly 30 percent less than the thickness of the corresponding impure carbonate facies. Shrinkage of such magnitude must have been accompanied by structural adjustments and may be related to some of the faults. Though it is not yet possible to reconstruct the structural history in detail, some of the faulting must have been later than the metamorphism because early metamorphic silicates were sheared before the ore was emplaced. Several large ore bodies occur near the edges of silicate masses where slumping due to shrinkage would have been most intense and most likely to yield broken ground.

The metasomatic or ore-forming stage that followed the metamorphic stage was probably a time of decreasing temperature. The ore minerals are generally accompanied by the relatively low temperature gangue minerals—chlorite, ferriferous tremolite, calcite, and quartz—which have replaced the earlier-formed diopside, garnet, and other relatively high temperature silicates. The silicated rocks far from ore bodies also show some retrograde alteration products that commonly, but not invariably, are associated with traces of ore minerals. These alteration products include serpentine derived from forsterite, tremolite and calcite derived from diopside, and quartz and calcite derived from wollastonite. The breakdown of diopside and wollastonite are clearly reversals of reactions that took place during the metamorphic stage.

Moore Ore Body Area.

The Moore ore body, which lies below the area of the geochemical study, was discovered by the Coronado Copper and Zinc Company in 1947 by core drilling. The company started to develop the body for mining by means of a new vertical shaft, the Moore shaft, and by an inclined winze from the Mammoth mine, which is southwest of the new ore body. Neither of the development workings had reached the ore when the Company suspended all operations in the district in 1949.

As indicated by drilling, the ore body is a lenticular mass near the top of the middle member of the Abrigo formation east of the Copper Chief fault and between 400 and 500 feet below the surface. Figure 2 is a detailed geologic map of the surface showing the location of ore holes and blank holes, and Figure 3 is a generalized cross section with nearby drill holes and ore intersections projected.

Several smaller ore bodies, also near the top of the middle member of the Abrigo formation, have been mined a short distance south of the mapped area. One of these, at the Copper Chief mine, about 1,500 feet south of the Moore ore body, was similar to the Moore ore body in shape and in location with respect to the Copper Chief fault. Others were west of the Copper Chief fault and included several tabular masses of the bedded type that were mined many years ago by extensive underhand stopes below the outcrop, and also two blind ore chimneys, both in the Mammoth mine. One chimney, mined during World War I, was a manto below the Old Manto fault. The other chimney, mined in very recent years, was almost parallel to the dip of the beds along the 467 fault.

Both these faults appear on the geologic map. The 467 ore chimney ended near the edge of the mapped area, the Old Manto ore body about 150 feet beyond the edge of the area. The ore shown by drill holes north of the Old Manto fault appears to be part of another very small unmined manto.

On the geologic map, Figure 2, the formations are subdivided on a lithologic basis in those areas where samples for geochemical analysis were collected. Most of the lithologic units correspond to stratigraphic units, but some limestone areas were formed by local alteration of dolomite beds, dedolomitization resulting from the reaction of silica with dolomite to form calcite and a magnesia-rich silicate, generally tremolite and less commonly forsterite or its alteration product serpentine. No evidence has been found anywhere in the Johnson district for the opposite process, dolomitization, which is common in some mining districts.

The beds in the Moore ore body area strike northwest and dip 30°–40° NE except in the arroyo along the northeast edge of the mapped area, where the dips are flatter and the strike shows local variations. The Copper Chief fault, a Northwester with east side down, is the largest of many faults in the area. East of it in the vicinity of the ore body the rock is broken by faults and fractures with several trends. Fractures are especially abundant in a triangular area between the Copper Chief fault and a north-trending fault that joins the Copper Chief fault about 850 feet south of the Moore shaft. Another intensely faulted and fractured area, separated from the first by a relatively unfractured band about 200 feet wide, is found in the Escabrosa limestone near the eastern edge of the mapped area. Considerable shifting of fault blocks is suggested by the pattern of limestone bands in the Escabrosa in this area, but no comparable offsets are apparent in the units of the Martin formation. This puzzling relation may be due to dying out of the faults or to their termination against a strike fault as suggested on the map. A third area containing many fractures is found several hundred feet west of the Copper Chief fault in the vicinity of coordinates N 11,600, E 5,700, where half a dozen small faults have been omitted from the map so that the geochemical data could be shown.

In the area of geochemical study east of the Copper Chief fault the oldest faults strike approximately east and dip south, generally at 30° to 60°. These Easters are commonly mineralized by narrow veins of quartz carrying iron oxides and occasional traces of copper minerals. Many faults that cut and offset the Easters range in strike from N 45° E to N 20° W and thus bridge the gap generally present in the district between Northeasters and Northwesters. These are normal faults, which dip more than 60° E or W and are represented by zones of breccia (Fig. 4) or sheared rock. Although some are locally silicified and rusty they are generally less silicified than the Easters.

The typical Northeasters of the district are commonly marked by small fissure veins of quartz, orthoclase, fluorite, calcite, and the ore minerals chalcopyrite, bornite, sphalerite, and locally tetrahedrite and galena. No veins of this type were found in the area of the geochemical study.

The geologic map (Fig. 2) shows the larger faults but does not show small fractures in the intervening fault blocks. The small fractures vary notably in abundance from place to place. They are much more common in dolomite than

in limestone, perhaps because dolomite acted as a brittle material, whereas limestone may have yielded by recrystallization or plastic flow. There seems to be a complete gradation from areas with no visible fractures other than wide-spaced joints to other areas where fractured ground merges imperceptibly into intensely sheared fault material. A fault that is a well-defined structure at one place may pass into a broad ill-defined zone of fractured rock in another part of its course. Much of the displacement in such areas took place through considerable widths of shattered rock and not along well-defined fault planes. Many of the approximately located faults shown on the geologic map are more or less arbitrarily located in zones of intense fracturing. In general, the density of faults shown on the map is a rough measure of the relative abundance of the smaller fractures.

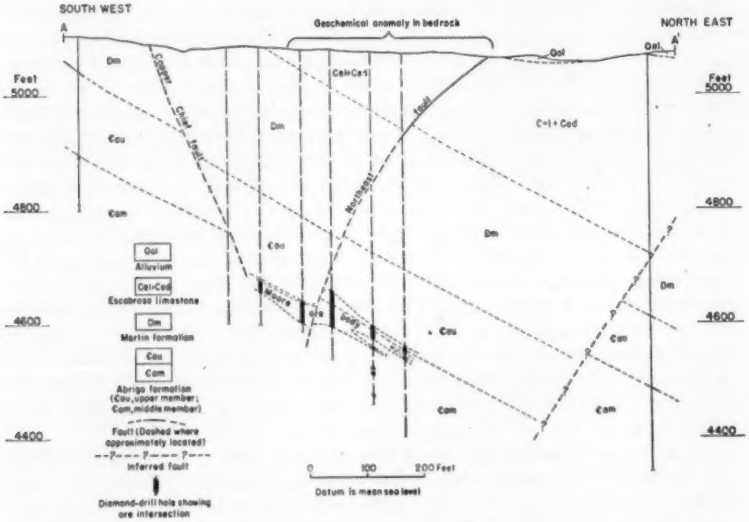

FIG. 3. Generalized cross section along the line indicated on Figures 1 and 2.

The cross section, Figure 3, is generalized as the diamond-drill holes do not provide enough data to work out the structure in detail. The large fault at the north end of the section is inferred from the apparent absence of upper units of the Martin formation in the drill hole in this area. The fault may be the extension of the east-trending fault zone exposed near coordinates N 11,640, E 5,750, which has about the same displacement, judging from evidence provided by the drill hole 300 feet northwest of the Moore shaft.

GEOCHEMICAL INVESTIGATIONS.

The Moore ore body area was selected for detailed geochemical study because much information on underground conditions there was available through

core drilling and yet the land surface is not much disturbed nor covered by mine dumps and buildings. Moreover, the Escabrosa limestone is well exposed above the ore; and as this formation is the most uniform lithologically of any formation in the area, geochemical data obtained on it should be relatively easy to interpret.

Sampling Procedure.

The first rock samples were collected in order to determine whether the metal content of the weathered surface of the rock was different from that of the unweathered rock. At each of 11 localities, two separate samples were collected, one composed of 5 to 10 chips from the weathered surface of the outcrop and the other composed of chips from the unweathered interior. The analyses of these samples, given in Table 3, show differences little or no larger than the

TABLE 3.

COMPARISON OF ORE-METAL CONTENT OF WEATHERED AND UNWEATHERED ROCK.

Location		Rock type	Total ore metal in parts per million	
N	E		Unweathered sample	Weathered sample
10,850	6,190	Hornstone	250	{250 300
10,885	6,160	Dolomite	{75 125	{200 200
10,940	6,160	Dolomite	50	50
10,965	6,130	Dolomite	50	50
11,040	6,140	Dolomite	50	75
11,090	6,130	Dolomite	{100 100	100
11,105	6,055	Dolomite	75	{50 100
11,145	6,115	Dolomite	75	{50 75
11,190	6,105	Limestone	50	50
11,230	6,065	Limestone	50	50
11,315	6,080	Limestone	50	50

Note: Braces indicate two separate analyses of a single sample.

error of analysis and indicate that surficial weathering has little effect upon the ore-metal content. To save sampling time all subsequent samples were taken with no regard to the amount of weathered surface in the sample; and subsquent analyses showed that this practice did not veil the systematic variations in the metal content of the samples.

Composite samples of about a dozen chips each were collected at intervals of about 50 feet along three traverse lines across the area. The analyses of these samples, shown in Figure 2, suggested that highly fractured rock had a higher-than-average metal content, presumably because metal-bearing fluids that penetrated the rock tended to follow the faults and fractures.

To test further the effect of fractures the next set of rock samples was taken by pairs, one sample of highly fractured or brecciated rock marking a fault and

another of the least fractured wall rock procurable within 6 feet of the fault. Thus each pair of samples represents extremes—the most fractured and the least fractured rock from essentially the same locality. The analyses of these samples shown in Figure 2, proved beyond any possibility of doubt that the abundance of fractures strongly affected the metal content of the rock; which in turn indicated that, unless samples contained fractured and unfractured rock in the same proportion as in the outcrop, a large "sampling error" would result and might obscure systematic areal variations of the ore metal.

The final set of rock samples was taken in a manner designed to make the samples representative of the area and at the same time to test the fault blocks for ore-metal anomalies. Small chips were collected every few feet along traverses that crossed the fault blocks. No chips were taken from the faults themselves but otherwise the samples include representative portions of the rock and whatever fractures it contained. Most of the samples consisted of 20 to 30 chips collected over a traverse of about 50 feet. The analytical results for these samples are also shown on Figure 2.

Soil samples were collected after a 1- to 2-inch layer of pebbles, plant material, and soil from the land surface was scraped off. The soil to be sampled was put through a 2-mm mesh stainless steel and aluminum sieve. Sampling was confined largely to low ridges where the soil was definitely derived from the local rock.

Sample Analysis.

Usually samples were collected in the morning and analyzed the same afternoon so that results would be available for guidance of more sampling the following morning. The rock samples, which averaged about 10 grams in weight, were ground to a fine powder with an iron mortar and pestle before analysis. The soil samples required no grinding. It was found that 25 to 30 rock samples could be collected, ground, and analyzed in an 8-hour day. Soil samples required less time in collection and preparation.

The analytical method used in the field was a primitive version of the general "heavy metal" test (4). Approximately ⅓ gram of the sample was measured with a volumetric scoop and digested in 4 ml of 1 : 3 nitric acid by keeping the solution at or near the boiling point for 10 minutes. The nature of effervescence, amount of residue, and presence of discoloration caused by iron were noted in the case of the rock samples, so that a rough estimate could be made of the relative amounts of calcite, dolomite, insoluble silicates, and iron in each sample. The determination was made as described in the reference given except that the buffer contained no fluoride and oxidation of the dithizone by iron gave some trouble in analyzing the soil samples. To eliminate any possible subjective influence in the colorimetric determinations, the procedure was arranged so that the source of the sample was unknown to the analyst at the time he made the analyses.

The reliability of the field analyses was checked in the Denver laboratory of the U. S. Geological Survey in two different ways: 1) by repeating the field analyses of all samples, using an improved procedure; and 2) by accurate determinations of copper, lead, and zinc in 37 selected samples. The field anal-

yses were repeated by Mr. J. J. Schuch, using weighed portions of the sample and digesting them in aqua regia. Determinations were made in the presence of fluoride to avoid interference by iron. The accurate laboratory determinations were made by Mr. Harold Bloom. As described in the reference given, the field test gives a positive reaction with any copper, lead, or zinc present in the sample. The results of the field test are expressed as parts per million of "zinc equivalents," which should correspond to zinc plus ½ of the copper plus ¼ of the lead. A comparison of the results obtained by the different analytical methods for the 37 samples analyzed by laboratory methods is presented in Table 4. The data from analyses based on the aqua regia extraction have been used in all the illustrations and interpretations; where two determinations were available for the same sample, an intermediate rounded-off value was used. As indicated by Table 4, the agreement of results from the various analytical methods used is fairly good, and even the original analyses made in the field were adequate to reveal significant differences among the samples.

TABLE 4.

COMPARISON OF RESULTS BY DIFFERENT ANALYTICAL METHODS, CONCENTRATIONS GIVEN IN PARTS PER MILLION.

Sample location		Description	Laboratory method			Zinc + ½Cu + ¼Pb	Field method	
N	E		Copper	Lead	Zinc		1:3 HNO	Aqua regia
Unmetamorphosed area		Limestone (Escabrosa)	10	10	10	17	50	50
Unmetamorphosed area		Dolomite (Escabrosa)	10	10	20	27	75	50
Unmetamorphosed area		Dolomite (Escabrosa)	10	10	15	22	75	75
Unmetamorphosed area		Dolomite (Martin, Dm6)	10	10	25	32	75	75
Unmetamorphosed area		Shale (Martin, Dm7)	10	10	20	27	50	50
Unmetamorphosed area		Sandy shale (Martin, Dm7)	15	20	25	37	50	75
12,325	4,950	Hornstone (Dm7)	140	10	35	107	150	75
11,880	5,325	Hornstone (Dm7)	40	10	20	42	100	75
11,515	5,550	Hornstone (Dm7)	115	10	110	170	100	250 150
11,240	5,760	Hornstone (Dm7)	115	10	40	100	200	100 125
10,850	6,190	Hornstone (Dm7)	410	10	35	242	400	300 250
10,840	6,235	Hornstone (Dm7)	100	10	25	77	50	100
11,310	5,700	Hornstone (Dm7)	20	10	24	36	75	75
11,005	6,570	Limestone (Escabrosa)	20	10	10	22	25	50
11,145	6,115	Dolomite (Escabrosa)	10	10	20	27	150	50 75
10,850	6,430	Dolomite (Escabrosa)	10	10	20	27	50	50
11,050	6,600	Fault zone in dolomite	190	10	165	262	400	250
11,050	6,600	Unfractured dolomite	15	10	40	50	125	50 75
11,400	5,760	Dolomite (Escabrosa)	10	10	10	17	50	50
11,110	6,075	Fault zone in dolomite	35	110	120	165	400	125 150

TABLE 4—*Continued.*

Sample location		Description	Laboratory method			Zinc + ½Cu + ½Pb	Field method	
N	E		Copper	Lead	Zinc		1:3 HNO	Aqua regia
11,195	6,255	Fault zone in limestone	15	10	15	25	50	50
10,600	6,350	Fault zone in limestone	40	10	20	42	75	75
10,840	6,780	Fault zone in limestone	1,280	1,500	1,760	2,775	800 1,000	2,200 2,400
10,905	6,455	Fault zone in limestone	1,100	1,190	1,060	1,907	1,000	2,000 1,600
10,840	6,570	Fault zone in limestone	680	8,000	1,550	3,890	1,200	—
10,375	6,580	Fault zone in dolomite	15	10	20	30	75	75
11,205	6,345	Dolomite (Escabrosa)	150	10	490	567	700	500
10,855	6,495	Dolomite (Escabrosa)	10	10	25	32	75	50
11,425	5,960	Dolomite (Escabrosa)	15	10	40	50	75	50
11,595	5,745	Dolomite (Escabrosa)	40	10	85	107	200	100 125
11,665	6,895	Dolomite (Escabrosa)	220	10	60	172	250	100 75
10,790	6,785	Dolomite (Escabrosa)	20	10	50	62	150	75 75
11,050	6,600	Soil near fault	640	30	1,080	1,407	1,000	1,000
11,410	5,770	Soil on dolomite	105	15	80	136	100	75 150
11,290	5,680	Soil on hornstone	380	20	140	335	150	275
11,055	6,010	Soil on hornstone	350	20	225	405	300	250
10,840	6,010	Soil on hornstone	460	25	170	406	400	100 200

Note: Braces indicate two separate analyses of a single sample.

Ore Metals in Bedrock.

Background Values.—Some ore metal is incorporated in sediment at the time it is deposited, and the amount of metal may be increased or decreased in the normal course of diagenesis and groundwater circulation. The resulting ore-metal content of the sedimentary rock is the background value. The background may vary from bed to bed and from place to place within a particular bed, without any relationship to hydrothermal processes of ore deposition.

The background values for the stratigraphic units sampled near the Moore ore body were obtained by sampling the same units on the northeast slope of Johnson Peak, about a mile west of the Moore ore body, in an area where the rocks are apparently unaltered. Each sample was a composite of chips taken every foot or so across the unit. Laboratory analyses of these samples, presented in Table 4, show 10 to 15 ppm of copper, 10 to 20 ppm of lead and 10 to 25 ppm of zinc; with a total "zinc equivalent" of less than 40 ppm in all samples. The corresponding field analyses show a 50 or 75 ppm "zinc equivalent."

Effects of Stratigraphy in the Mineralized Area.—It is obvious that ore bodies in the Johnson district have selectively replaced particular beds. Available geochemical evidence indicates that traces of ore metals were similarly con-

centrated in particular beds and rock types. In the metamorphosed area, 175 bedrock samples, excluding fault-zone samples, were analyzed for total ore metal (Fig. 2). Of these, the limestone samples average 67 ppm in metal; the dolomite samples average 100 ppm; the hornstone samples average 150 ppm. Selective deposition in dolomite and hornstone is indicated. At five localities samples were taken on opposite sides of faults that separate limestone from dolomite, with the following results:

Location	Limestone	Dolomite
N 11,660 E 6,022	125 225	350
N 11,660 E 6,002	125	600
N 11,375 E 6,035	50	75
N 10,823 E 6,573	50	75
N 10,850 E 6,595	50	75

Note: Brace indicates two separate analyses of a single sample.

The metal content at the first two localities is definitely above the background content and shows preferential deposition in the dolomite. The selective concentration in particular rock types may be due to differences in permeability or some unknown chemical effects. For the purpose of geochemical prospecting, at least in the Johnson area, the explanation is not so important as the empirical facts that the percentage of ore metal in one rock type is not directly comparable with that in another and that some rock types are more sensitive indicators of areas with introduced metals. The facts suggest that the heart of a geochemical anomaly may be located by examining progressively less susceptible beds.

The importance of stratigraphy goes beyond broad lithologic distinctions like limestone and dolomite. A dolomite bed that contains small masses of silicates derived from chert nodules is particularly rich in ore metals. The once cherty bed is about 10 feet thick and may be traced from the northeast-trending fault near N 11,225, E 6,300 to the north trending fault near N 11,060, E 6,600. The three prospect pits in this area are all in this bed, which shows some copper stain, particularly in the metachert nodules. Chip samples across the bed, taken where no copper minerals were apparent, yielded 500, 400 and 300 ppm respectively, the maximum values obtained in any of the chip samples taken along traverses. Some metachert nodules, which may indicate the same bed, were noted for about 150 feet northwest of the prospect at N 10,645, E 6,985. This area is also one of the very few places within the map limits where ore minerals are visible.

The stratigraphy must be borne in mind in any future geochemical studies that may be undertaken in the district. This study provides a basis for interpreting results in the small part of the stratigraphic section studied. It is expected that higher beds, at least those of the Escabrosa limestone, will yield results that are comparable with those obtained from dolomite and limestone units already studied, for these beds are similar in lithology and in type of alteration. The lower beds constitute a different and far more difficult problem because the rocks below the stylolitic dolomite unit (Dm6) are very diverse lithologically. They are much altered mineralogically in a large area surround-

ing the mines and contain small quantities of visible ore minerals in many parts of the altered area.

Concentration in Fault Zones.—The concentration of ore metals in certain fault zones is an incontrovertible fact revealed by this geochemical investigation. The data, presented in Figure 2, show that fault zones contain up to 2,300 ppm ore metal even though unfractured dolomite several feet away may contain only 75 ppm, the background value. Metal is concentrated in every type of fault material sampled. The fault material sampled included breccia (Fig. 4) and intensely sheared or sheeted rock both with and without introduced silica and iron; soft fault gouge, found in some of the mine workings of the district, is nowhere exposed in the area studied geochemically and therefore was not sampled. Quantitative estimates made in the course of chemical anal-

FIG. 4. Fault zone marked by breccia.

ysis and presented in Table 5 show that, on the average, faults rich in insoluble matter, iron and secondary calcite are higher in ore metal than the rest, but that each kind of fault material contains both high and low values. Field observations lead to the same conclusion, for experience has shown repeatedly that faults, which appear to be similar in every way, may range in richness from a very high metal content to a background metal content.

The concentrations are not confined to any particular set of faults; they may be different in two parallel faults and in one part of a particular fault as contrasted with another part. The Copper Chief fault contains from 75 to 600 ppm ore metal, and other faults show comparable variations along their course. The greatest concentrations were found in thin, silicified and rusty Easters;

and the Easters average somewhat higher in metal than the rest. In general, the introduced metals are copper and zinc, but several faults are surprisingly high in lead (Table 4). The metals are the same as those contained in visible minerals found in quartz veins along some Northeasters in the district. The commonest ore minerals in such veins contain copper and zinc, but lead minerals are present locally.

It is not surprising that fault zones contain abnormally large quantities of heavy metals. Fault fissures were evidently channels for mineralizing solu-

TABLE 5.

RELATION BETWEEN ORE-METAL CONTENT AND MAJOR CONSTITUENTS OF SAMPLES OF CARBONATE ROCKS.

		Pure or nearly pure carbonate				High insoluble residue, little or no iron				High insoluble residue and iron			
		Number of samples	ppm of ore metal			Number of samples	ppm of ore metal			Number of samples	ppm of ore metal		
			Min.	Max.	Average		Min.	Max.	Average		Min.	Max.	Average
Fault-zone samples	Carbonate dominantly calcite	7	100	500	211	3	50	100	75	13	100	2,300	698
	Carbonate dominantly dolomite	11	75	275	125	10	75	600	252	16	75	1,800	361
Wall-rock samples	Carbonate dominantly calcite	12	50	175	69	0				1	50	50	50
	Carbonate dominantly dolomite	43	50	600	86	3	50	225	117	1	50	50	50
Traverse samples	Carbonate dominantly calcite	15	50	150	77	0				0			
	Carbonate dominantly dolomite	56	50	500	106	9	50	400	164	0			

tions in the district because ore bodies are found along them and because ore minerals are visible in them at some places. The chief problem in prospecting for new ore is to tell which fissure or which part of a fissure was a channelway for mineralizing solutions and, therefore, where ore may be localized in the favorable beds. A concentration of ore metals in and near a fissure is certainly a good indication of a channelway at the ore-forming stage. Exposures of the 467 fault above the 467 ore chimney in the Mammoth mine contain visible copper minerals, and fissures in the Escabrosa limestone above the large ore bodies of the Republic mine also contain visible copper minerals. Chemical tests for

ore metals are much more sensitive and accurate than visual examination in measuring the concentrations. The samples in the Copper Chief fault zone at N 11,660 are the only ones taken where any ore minerals were visible. This is the only place on all the faults sampled that would be noted visually as favorable for prospecting. The chemical data, however, permit all the faults to be evaluated quantitatively in terms of contained ore metal. They reveal that several faults with no visible ore minerals have an even higher metal content than the fault with visible ore minerals.

Other criteria used to recognize fractures that have been channelways for ore solutions and may have localized ore bodies in the favorable beds are the presence of quartz and of iron stain. Neither of these criteria is reliable, as indicated by the geochemical data. Although silicified and rusty faults showed the highest concentrations of ore metal, some equally silicified and rusty faults yielded only background values.

Concentrations in Fractured Rock.—The blocks between the faults shown on the geologic map are cut by minute fractures, some of which have seams of quartz or calcite. These small fractures and seams, like the larger faults, are places where ore metals are concentrated, as shown by a comparison of the analyses of unsheared rock next to faults with the analyses of nearby chip samples collected along traverses (Fig. 2). In general the geochemical highs in bedrock, indicated by the traverse samples, are in much-fractured areas, but some equally fractured areas yield only background values and some areas without evident fractures are notably mineralized. The highs are not marked by visible peculiarities, but are revealed only by chemical analysis. As in the faults, the principal ore metals involved are copper and zinc.

Pattern of Distribution.—Figure 5, a and b, shows the general relation of known ore in depth to ore-metal determinations in fault zones and intervening fault blocks at the surface. To facilitate the graphic presentation, the analyses are simply classified as + or −, depending upon whether they show values higher or lower than an arbitrary value. The pattern given by the fault-zone samples is somewhat erratic and does not correlate with underlying ore in detail. It seems clear that at the horizon of the present land surface, metal-depositing solutions leaked along faults over a larger area than the one investigated. Fault-zone studies of this kind may prove most useful in outlining broad areas favorable for prospecting.

Geologic relations not shown in Figure 5 must be considered in interpreting the fault-zone data. For example, the three background values over the northern edge of the Moore ore body, though in an area where leaks from the ore body would be expected, were obtained from faults in limestone, a rock that tends to be "tight" and to have a low metal content. The seven background values south of the ore body all came from faults in dolomite, a better host rock, and thus give a sounder basis for concluding that they indicate a truly unfavorable area for prospecting. The abundance of high values in the area east of the Moore ore body is noteworthy; the geologic structure would permit leaks from the Moore ore body in this direction but it is unlikely that the whole anomaly is related to that ore body as now known, for this would mean that the metal-bearing solutions had crossed several late and persistent fault channels

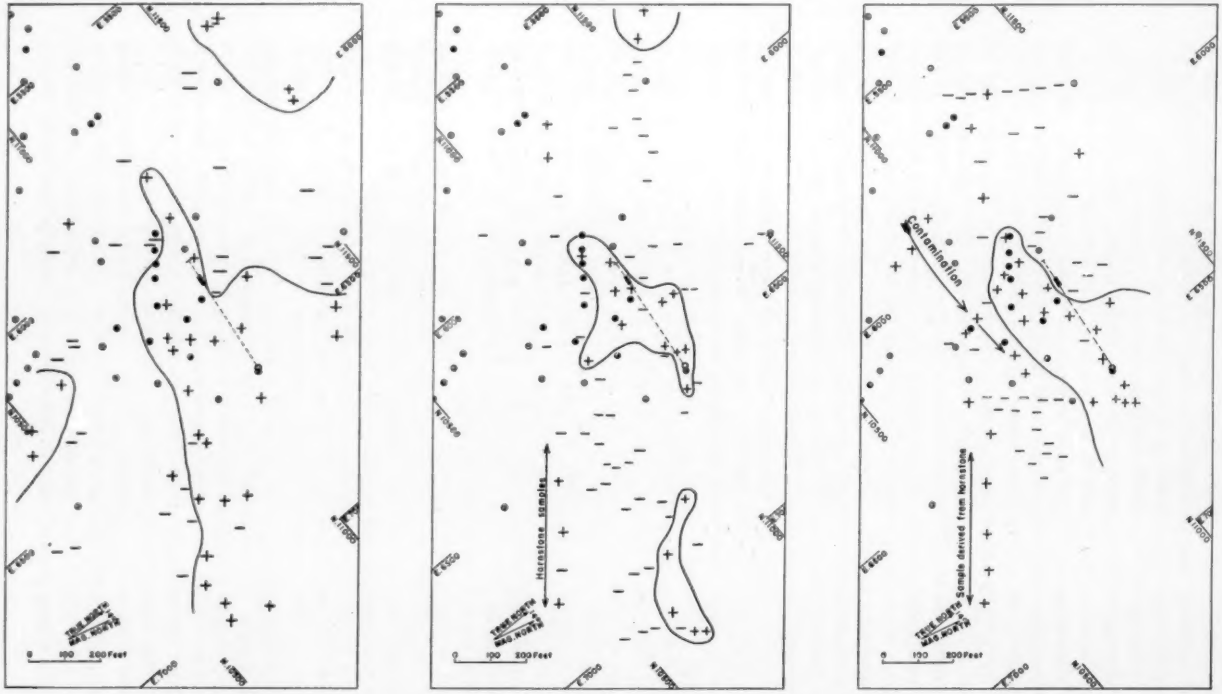

FIG. 5. Sketch maps showing relation of geochemical anomalies to known ore in depth. Diamond-drill hole symbols same as in Figures 1 and 2. (a) anomaly based on analyses of fault samples; + indicates metal concentration of 175 ppm or more and — indicates 174 ppm or less; (b) anomaly based on analyses of chip samples collected along traverses; + indicates a metal concentration of 125 ppm or more and — indicates 124 ppm or less; and (c) anomaly based on analyses of soil samples; + indicates a metal concentration of 350 ppm or more and — indicates 349 ppm or less.

across the trend of the anomaly. Some of the high values in the area west of the Moore ore body may be related to other ore bodies. For example, high values were obtained from the 467 fault and Old Manto fault, both of which are associated with ore bodies a short distance outside the map area. High values were also obtained in the northern part of the mapped area; there is no reason to suppose that these are related to any ore body now known.

The ore-metal content of the rock between the faults, indicated by the analyses of chip samples taken across the fault blocks, provides a basis for locating areas particularly promising for prospecting (Fig. 5b). As with the fault-zone data, the stratigraphy and structure, which are not shown on Figure 5, must be considered in interpreting the results. For example, the hornstone, which tended to collect ore metal, is expressed by a band of predominantly high values along the southwestern side of the mapped area. Ignoring this band of high values, which seems to be simply an expression of the stratigraphy, two conspicuous anomalies remain. The larger one of these overlaps the Moore ore body and extends east of it to the overlapping alluvium. A spatial and genetic connection between the ore body and the geochemical anomaly seems probable. Another anomaly centers about 700 feet southeast of the first and also extends eastward to the overlapping alluvium. Each of these anomalies contains a small area with visible copper minerals, and these visibly mineralized portions mark areas in which samples of apparently unmineralized rock are very high in ore metals. The high values seem to be related in part to the presence of cherty dolomite, as previously pointed out, but cannot be explained wholly in this way for they are in several beds, including limestone and noncherty dolomite. In the southeastern anomaly, the very high values may be related to an east-trending fault that dips 54° to 60° S and contains chrysocolla and malachite in the prospect at N 10,700, E 6,960. There may be an analogy in the northwestern high, where the best showing of copper at the surface is also in an Easter exposed in the prospect at N 11,205, E 6,320. Though this Easter cannot be traced at the surface and may not be a through-going structure, its projection points toward the Moore ore body.

Another anomaly is indicated in the northern part of the mapped area by high values in faults and unsheared wall rock near the Copper Chief fault, and in the fractured outcrop several hundred feet farther west (Fig. 2). It was impossible to investigate this anomaly fully in the time available.

Desirable Future Investigations.—This study shows that geochemistry may be a valuable tool in prospecting for concealed ore bodies in the district. The geochemical method certainly merits additional investigation. Additional work could follow either or both of two approaches; both are desirable and the two might be followed simultaneously. One approach is to explore beneath the surface geochemical anomalies by diamond drilling or some other means to see if anomalies are always or generally associated with ore in depth; the other is to investigate the vertical extent of the geochemical anomalies to see if there is a continuous connection between the surface anomaly and the ore.

The best prospect for exploration in the area studied is the anomaly about 750 feet southeast of the Moore ore body (Fig. 5b). This area is similar to the Moore ore body area both in geologic structure and in ore-metal distribution. The most promising place to start exploration is probably several hundred feet

southwest of the center of the anomaly. This suggestion is made because of the direction and amount of offset between the Moore ore body and the geochemical anomaly apparently related to it, and because of the apparent importance of a south-dipping Easter in localizing maximum deposition of ore metal in the project area. It should be emphasized, however, that the course of mineralizing solutions in any particular area must have been controlled by the local geologic structure. All parts of the much-fractured area east of the large fault running approximately along E 6,600 must be considered favorable ground until more is known about the geologic structure and its effects on movements of solutions.

On the geochemical side, it would be desirable to study the drill cores from the Moore ore body area to get all possible information on the location and behavior of the geochemical anomaly in depth. Geochemical anomalies should be sought and mapped in the vicinity of other ore bodies in the district by studies of both surface samples and underground samples procured from mine workings and drill cores. In some limited area, say the Moore ore body area, the fault zones should be sampled every 5 or 10 feet and the beds at somewhat greater intervals to determine whether variations in ore-metal content are uniform or erratic, and thus whether close-spaced sampling is required to give a reliable picture.

Soil Studies.

If it can be assumed that the ore-metal content of the soil is related to the ore-metal content of the rock from which the soil is derived, then soil analysis offers a means of detecting higher-than-average metal content in the bedrock. Soil studies involve several problems not present in rock studies; however, the problem of obtaining representative samples is somewhat simplified.

Typically, a soil is derived not only from parent rock immediately underneath but also from material that has migrated downhill under the influence of gravity during the process of weathering and erosion. Consequently, the ore-metal content of the soil may be related more closely to the metal content of rock on the hillside above than to the metal content of the underlying rock. In the process of soil formation considerable mixing is involved so that it would be futile to try to distinguish soils derived from unfissured rock, fissured rock, and fault or vein rock because these rock types are so closely associated areally. However, the mixing during soil formation is advantageous in some respects; for a small sample of soil is a naturally mixed sample representing a considerable mass of parent rock.

Soil samples collected on the hillside southwest of the Moore shaft at coordinates 10,970 N, 5,870 E; 10,890 N, 5,910 E; and 10,820 N, 5,920 E, have total metal contents of 1,000, 700, and 600 ppm, respectively. These soils rest on dolomite with a relatively low metal content. Ore-bearing Abrigo formation crops out and is exposed in old surface workings near the crest of the hill to the southwest of the mapped area. From the distribution of float containing ore minerals around these old workings it is obvious that copper- and zinc-rich soil materials are migrating downhill toward the sites sampled and explain their high metal content. Similarly, all soils downhill from known ore deposits or workings may be expected to be contaminated to a greater or lesser extent by

slope wash from these ore deposits. To avoid such contamination soil sampling was restricted largely to areas so situated topographically that such contamination is very unlikely. Sludge from diamond-drill rigs and ore dropped along roads are other possible sources of contamination. Sample sites were selected where contamination of this type is unlikely.

A tailings pond at the Republic Mill, about 1.5 miles south of the area shown in Figure 1, is still another possible source of contamination. On windy days dry tailings are blown about and are undoubtedly incorporated in neighboring soils. The extent to which this aeolian contamination has affected the soils is unknown. However, if the contamination is widespread it must be comparatively low in magnitude because many of the soil samples have a low metal content.

Samples of soil that could not be contaminated by slope wash correlate crudely in metal content with the rock nearby. In general the metal content of the soil is several times that of the corresponding rock. Most of the soils sampled were derived from limestones and dolomites of varying purity. They weather largely by solution of their carbonate constituent and the resulting soils are relatively carbonate-poor. In general the soil seems to represent the insoluble residue of the limestone or dolomite, and the ore metal appears to remain in the residue. Apparently even the small trace of the ore metal present is insoluble enough under the prevailing climatic conditions so that it is not leached away by ground water. This conclusion substantiates observations of the behavior of copper upon weathering at San Manuel (5).

The correlation between the metal content of the soil and of the bedrock is poorest for soils from the non-carbonate hornstone bed in the Martin formation. Possibly the poor correlation is due to the manner of weathering of the hornstone, which breaks up into resistant blocks with few small fragments.

The correlation between the metal content of the soil and that of the bedrock is best for soils derived from the carbonate rocks. In Figure 5c an ore-metal anomaly above the Moore ore body shows some of the characteristics of both fault-zone and traverse-sample anomalies. The correspondence between these anomalies not only indicates that there is a relationship between metal content in soil and bedrock but also confirms the existence of an anomaly in the vicinity of the hidden ore body.

It seems likely that in many places chemical prospecting for anomalies of this type can be accomplished by either soil or rock analysis. Soil study offers advantages in ease of sampling and preparation but the disadvantage of soil contamination. Soil studies may prove especially valuable in reconnaissance work and in areas where outcrops are scarce. It seems obvious that both rock and soil should be studied until more is known about geochemical prospecting, so that the results obtained by one approach can be checked against the results obtained by the other.

CONCLUSIONS.

In the area investigated, the copper, zinc, and lead content of the rock varies markedly because of inherent differences in the original rock and differences in the amount of metal subsequently introduced. The factors determining the amount of introduced metal include lithology and kind of alteration of the

original bed, amount of fracturing, and geographic position. After discounting the factors that can be evaluated by careful geologic study—lithology, kind of alteration, and amount of fracturing—anomalies remain. One of these anomalies seems to be related to the Moore ore body, which is about 400 feet beneath the surface. Therefore, geochemistry is regarded as a promising tool in exploring for other concealed ore bodies in this and similar districts.

The beds investigated include relatively pure limestones and dolomites of the Escabrosa and Martin formations and a shale bed in the Martin. The carbonate beds both outside the mining district and at many places within the district average out 20 ppm zinc, 10 ppm copper, and 10 ppm lead. This small background metal content seems to be syngenetic and thus unrelated to the ore deposits of the district. The background metal content of the shale bed is about the same as that of the carbonate rocks.

In the area of special study near the Moore ore body, the ore-metal content correlates to some extent with particular beds or particular rock types. For example, limestone generally contains less metal than dolomite, both where the values are very low and apparently due to slight differences in the background and where the values are higher and indicate introduction of metal from mineralizing solutions. The introduction into dolomite in preference to limestone may have been due to differences in permeability resulting from differences in behavior of the two rocks under stress; dolomite seems to have been brittle, for it is much fractured and hence relatively permeable; whereas limestone seems to have yielded partly by recrystallization or plastic flow, for it is less fractured and hence presumably less permeable. Particularly high concentrations of metal, up to 490 ppm zinc (24 times background) and 150 ppm copper (15 times background, were found in a once-cherty dolomite bed in which the chert nodules are now represented by aggregates of contact-metamorphic silicates. This bed is one of the few in the area investigated where any ore minerals are visible. The visible ore minerals are chrysocolla and malachite, but the bed is not particularly high in copper. Samples from areas where no ore minerals are visible contain up to 1,280 ppm copper (128 times background). It is concluded that the ore-metal content of these rocks cannot be determined by visual examination; it can be determined only by chemical analysis.

Fault zones carry the highest concentrations of ore metal, concentrations much higher than the background. Accurate laboratory analyses have shown concentrations up to 1,760 ppm zinc (88 times background) and 1,280 ppm copper (128 times background). Anomalously high lead values are present in a few samples. The metal content varies markedly; it ranges from 75 to 600 ppm along one fault. On the average, the east-trending faults and faults high in insoluble material, iron, and secondary calcite are somewhat higher in ore metal than the rest; but there is no clear-cut correlation between the amount of ore metal and either the attitude of the fault or the character of the fault material. Chemical analyses have shown repeatedly that faults of identical appearance may have a very high or only a background metal content, or any metal content between those two extremes. The data available indicate broad anomalies in which all the fault zones are high in metal. The Moore ore body is beneath such an anomaly, which is considerably larger than the ore body.

In general, there was little impregnation of ore metal into unfractured rock near the faults. A fault zone with as much as 2,300 ppm ore metal may be only a few feet from unfractured wall rock that contains no more than 75 ppm ore metal, the background value. However, the rock between the faults locally contains concentrations of metal along minute fractures. The mere presence of fractures does not necessarily entail concentration of metal. Some highly fractured areas have the background content of metal, whereas some little-fractured areas contain notable concentrations.

The analyses of chip samples taken at short intervals along traverses show the average metal concentration of large fault blocks. One of the anomalies determined by chip sampling is above the Moore ore body but displaced somewhat to one side. A genetic relation is suggested by proximity and by the occurrence within the anomaly of metal-bearing fault zones that project toward the ore. Other chemical anomalies are present in areas which have not been explored and below which the presence or absence of ore is unknown. Underground exploration of these areas and further geochemical work are suggested as means of proving or disproving genetic relationships between ore bodies and geochemical anomalies of this type.

The sampling and analysis of soil also can be used to locate geochemical anomalies. The ore-metal content of the soil is higher than that of the limestone or dolomite from which it is derived; this probably is the result of residual concentration of copper and zinc with other insoluble rock constituents when the carbonates are dissolved and leached away by ground water. The mixing of soil during weathering and erosion makes soil samples more representative than bedrock samples. However, the soil samples may be contaminated by soil-forming materials from higher on the hillside. The analysis of apparently uncontaminated soil samples confirms the presence of a geochemical high over the Moore ore body.

The sampling and field analytical methods used during this investigation are simple and rapid. Two men can easily collect and analyze, in a field laboratory, from 25 to 30 samples a day.

U. S. GEOLOGICAL SURVEY,
DENVER, COLORADO,
April 22, 1951.

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GEOLOGY OF KYANITE DEPOSITS AT HENRY KNOB, SOUTH CAROLINA.[1]

LAURENCE L. SMITH AND ROY NEWCOME, JR.

ABSTRACT.

Commercial deposits of kyanite occur in massive quartzite that constitutes the principal rock of Henry Knob, a conspicuous monadnock, three miles west of Clover, South Carolina. The deposit is a disseminated type consisting of simply kyanite-rich quartzite. Deposition was accomplished by hydrothermal solutions which presumably emanated from a nearby granitic intrusion. Circulation of the solutions was largely controlled by superior permeability of the quartzose rock.

INTRODUCTION.

THE occurrence of kyanite at Henry Knob was mentioned as long ago as 1846 by Michael Tuomey [2] who was then State Geologist of South Carolina. The possible commercial value of these deposits was suggested in 1932 by the senior author [3] of this paper and at about this time an initial shipment of the kyanite rock was made for testing purposes. When field work for this study was begun in September 1948, Commercialores Incorporated had under construction a plant for processing the rock and open-pit operations began soon thereafter.

The original field work for this study was done by the junior author during the winter of 1948–49. At that time a small quarry which was being cut across the knob near its summit exposed some of the deposit and associated rocks but neither the complete thickness of the mineralized body nor its relation to the country rock was revealed. Much of the geology of the rocks surrounding the kyanitic quartzite is obscured by severe metamorphism and deep weathering, together with an abundant talus which has accumulated on the flanks of the knob. More recent quarrying operations have uncovered pertinent facts which were not available when this study was first pursued.

The writers are grateful for courtesies and cooperation received from Mr. Eckels and other officials of Commercialores Incorporated.

TOPOGRAPHY.

Henry Knob is one of the numerous monadnocks in the Carolinas which stand above the dissected surface of the Piedmont. It is located in York County, South Carolina, two miles south of the North Carolina-South Caro-

[1] Originally submitted in part by Roy Newcome, Jr., as an M.S. Thesis, University of South Carolina.

[2] Tuomey, Michael, Report on the geology of South Carolina, p. 78, 1848.

[3] Smith, Laurence L., The nonmetallic mineral resources and their value to South Carolina: Pit and Quarry, vol. 24, no. 9, p. 31, 1932.

lina boundary and three miles west of the town of Clover. Five miles to the northwest is the summit of the better known and historically famous Kings Mountain.

The topography of this area is characteristic of that which prevails throughout the interior part of the Piedmont. The surface in general is mildly dissected and elevations range between 700 and 900 feet. Henry Knob rises abruptly from 900 feet at its base to an elevation of 1,250 feet at the summit. This strikingly conical monadnock covers approximately one quarter square mile.

GENERAL GEOLOGY.

Henry Knob is situated near the eastern edge of the Kings Mountain quadrangle which has been mapped by Keith and Sterrett.[4] Most of the rocks have suffered intense metamorphism and severe folding. All structures

FIG. 1. Henry Knob from the east showing quarry near summit.

trend in a northeast-southwest direction and in most places the angles of dip and formational contacts are near vertical. The rock types in the vicinity of Henry Knob are much fewer in number and accordingly the geology is much simpler than that which one encounters farther west and beyond Kings Mountain.

Roan Gneiss.—This is the oldest rock that occurs in the immediate vicinity of Henry Knob. It consists principally of dark hornblendic schists, gneisses and diorites. Some phases are altered intrusions which have invaded the older Carolina gneiss, a rock group which, although widespread throughout

[4] Keith, Arthur, and Sterrett, Douglas B., Description of the Gaffney and Kings Mountain quadrangles: U. S. Geol. Survey Geol. Atlas 222, Gaffney-Kings Mountain folio, South Carolina-North Carolina, 1931.

the Piedmont, is not found in the Henry Knob locality. Both the Carolina gneiss and the Roan gneiss were considered by Keith and Sterrett to be Archeozoic in age.

Bessemer Granite.—This is the most extensive rock type in the area. Keith and Sterrett regarded it as an Archeozoic intrusive and show it flanking Henry Knob on all sides and underlying a four-mile wide belt to the northeast and southwest. The original granite is so thoroughly metamorphosed that in most places it is unrecognizable as such and is more accurately described as a schist. Ready recognition is further obscured in most outcrops by deep weathering which has produced a friable saprolite. The direction of the schistosity is 40 degrees east of north and dips are near the vertical.

Microscopic examination of relatively fresh specimens of the schistose granite from an outcrop one mile north of Henry Knob shows quartz, muscovite and biotite as the principal minerals with subordinate amounts of orthoclase and chlorite. Small quantities of pyrite, garnet and zircon are also present.

Kings Mountain Quartzite.—Henry Knob marks the northern extremity of a long narrow gently-curved body of quartzite and schist called Kings Mountain quartzite. This formation extends southwest from the knob for nearly two miles and appears to have a rather uniform width of approximately 250 feet. Farther northeast it reappears to form the crests of the Pinnacle and Crowders Mountain. Keith and Sterrett listed this formation under their Cambrian group and divided it into three distinct facies, namely an angular-grained white quartzite, a chlorite-sericite schist, and a kyanitic quartzite. Only the last two types are found at Henry Knob.

Kyanitic quartzite forms the core of Henry Knob and constitutes the rock now being quarried. This rock, where fresh, is bright gray in color and contains considerable pyrite in addition to quartz and kyanite. Near the surface the pyrite has weathered to limonite thus leaving voids and brownish stains. The texture is fine and the structure displays no discernible bedding. Vertical and horizontal joints, spaced three to six feet apart, facilitate removal of the rock and have produced talus blocks along the slopes and near the base of the knob.

The schist member is essentially a quartz-sericite metamorphic. No chlorite is to be found in the highly weathered rock now accessible in the quarry. It contains less kyanite than the quartzite and all of the original pyrite has altered to limonite. This schist bounds the quartzite and crops out along the flanks of the knob. One layer twenty and another ten feet thick are interbedded with the kyanitic quartzite. Contacts between the two are sharp and vertical in position. Whether or not lateral gradations occur cannot be determined. There are some suggestions that the interbedded bodies of schist may represent granitic intrusions, but the rock now exposed is so highly altered that conclusive evidence of its original nature is not at hand. However, it is believed to have been derived from a more argillaceous sediment than that which crystallized into quartzite and that the two are simply varying facies of an ancient deposit.

Yorkville Granite.—This intrusive is exposed over a large area south and

southeast of Henry Knob with the nearest outcrops slightly over a mile distant. It is a medium gray, coarse-grained rock consisting of microcline, orthoclase, oligoclase and quartz with small amounts of biotite and muscovite and a little garnet.

The Yorkville granite is considered to have been intruded in late Carboniferous time during or closely following the Appalachian folding. Presumably the mass broadens in depth and underlies much of the older rocks now exposed in the vicinity of Henry Knob.

Diabase Dikes.—One of many diabase dikes in the Kings Mountain quadrangle cuts the southeast end of Henry Knob. It is about 100 feet thick and extends for several miles in a northwest-southeast direction. The trend and the mineral composition simulates that of numerous similar intrusions of the southern Piedmont which are generally assumed to be Triassic in age. The dike has no relation to the genesis of the kyanite deposits.

EXTENT AND STRUCTURE OF THE KYANITE DEPOSITS.

Workable deposits of kyanite are restricted to the quartzite of which there is a total thickness of over 100 feet showing in the quarry on Henry Knob. Interbedded schists divide the quartzite into three parallel bodies. A central zone of quartzite is separated from a smaller one on the southeast by about

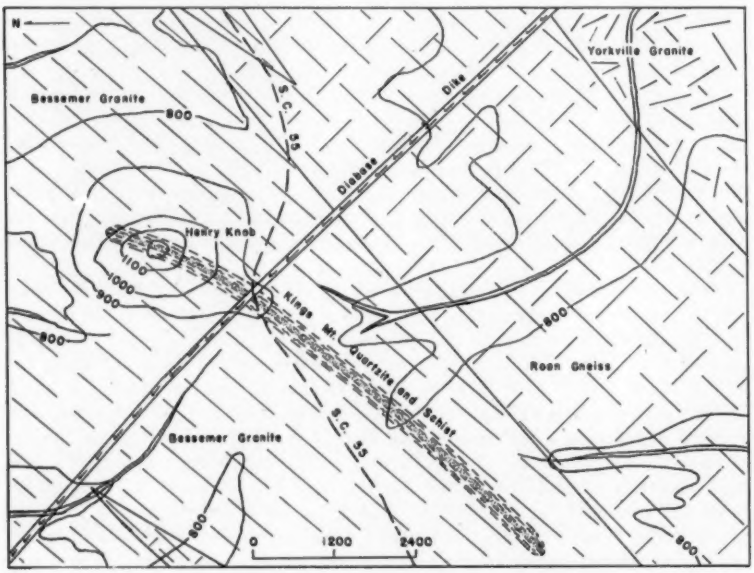

FIG. 2. Geologic map of area in vicinity of Henry Knob. Modified from Keith and Sterrett.

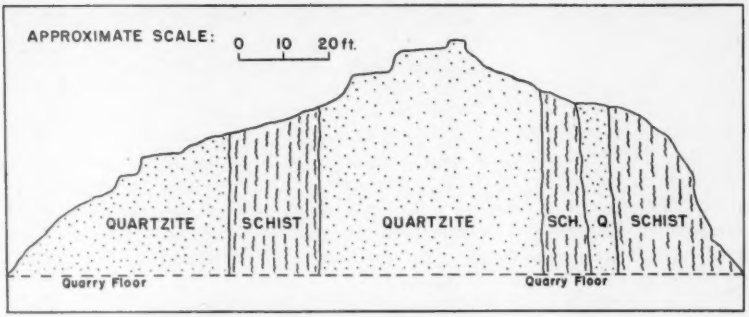

FIG. 3. East-west cross section along quarry face.

ten feet of schist, and in turn twenty feet of schist intervene between it and a quartzite body on the northwest which has a minimum exposed thickness of fifty feet (Fig. 3). Presumably the thicknesses of the bodies of commercial rock vary both in depth and along the strike and with the disappearance of the intervening schist, the three quartzite zones may merge into one body. Kyanite-rich quartzite can be traced to the southwest from the quarry for a distance of two miles (Fig. 2). The zones of interbedded schist carry from ten to twelve percent of kyanite whereas the quartzite averages over twenty percent. Test drilling to depths of 200 feet has shown no variation in the kyanite content.

Uniformly massive structure prevails throughout the quartzite and no bedding has been observed. Indistinct jointing is accentuated near the surface by limonite stains and is evidenced in fresh rock when blocks are loosened by blasting. Contacts with interbedded schist are sharp and nearly vertical in position. If these contacts represent junctures between two originally different sedimentary facies then the quartzite, whose bedding though obliterated by metamorphism, must have a vertical position. Further evidence of such structure is suggested by occasional vertical streaks of pyrite which appear to have been deposited along original bedding planes.

PETROLOGY AND PETROGRAPHY OF THE KYANITIC QUARTZITE.

The quartzite is strikingly uniform in color and texture and is simple in mineral composition. No minerals other than quartz, kyanite and pyrite have been found.

Quartz forms a mosaic structure in which most crystals range from 0.2 to 0.5 mm in diameter. Occasional areas composed of uniformly smaller crystals appear to represent variations in the original sediments. Much of the quartz shows undulatory extinction. Vug-like cavities, mostly from 1 to 3 mm in diameter and probably formed by circulating hydrothermal solutions, are abundant in some of the rock. Euhedral kyanite and subhedral crystals of pyrite partially line such cavities.

Kyanite is, in general, quite uniformly distributed and constitutes over twenty percent of the quartzite. It is lacking in some small local areas while others contain as much as eighty percent. The average lengths approximate 0.5 mm and in general the color varies from medium gray to faint blue with clear colorless crystals predominating in the vugs. Bladed forms commonly showing cleavage are general and some exhibit twinning. Single kyanite crystals may enclose a swarm of quartz grains. Such inclusions are particularly abundant near the margins and become both smaller and fewer in number near the middle of the host (Fig. 4). The quartz inclusions of the peripheral areas are smaller than those of the quartzite groundmass while the centers of many host crystals are free of them. Obviously, the kyanite metacrysts have grown by progressive replacement of quartz.

Most kyanite is unoriented but in places a semblance of parallelism of the crystals can be seen. Such lineation is nearly vertical and presumably parallels the original bedding of the host rock. This feature is more conspicuous

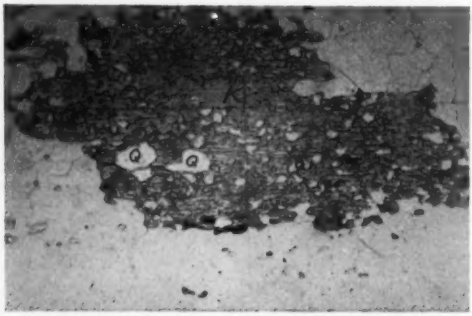

FIG. 4. Thin section showing kyanite replacing quartz. × 35.

on weathered surfaces where the sharp blades of kyanite stand out in relief. Some long blades are bent and others are disrupted with wedge-like grains of quartz enclosed between cleavage pieces. Kyanite in the schist is associated and intergrown with sericite, both minerals giving fissility to the rock.

Minute seams of kyanite occur along the contact of quartzite and interbedded schist. This juncture has served to concentrate a thin mat of crystals which have grown with their long dimensions oriented roughly parallel to it.

Veins containing kyanite have recently been found by workmen but have not been seen in place by the writers. A section of one such vein about two inches thick contains the same minerals as the quartzite although apparently in different proportions. Kyanite crystals are in the form of faintly bluish to clear blades one inch in length and appear to be in greater abundance than those disseminated through the quartzite. The quartz crystals are clear and subhedral in form. Insufficient pyrite was retained for satisfactory observation.

Pyrite occurs as irregular grains and subhedral combinations of pyritohedrons and octahedrons generally from 0.5 to 1.0 mm in diameter. Crystals are smaller in the finer grained quartzite. It transects kyanite, forms wedges along its cleavage, and even includes small rounded grains. The distribution and variation in quantity throughout the quartzite simulates that of kyanite. This suggests that though later in sequence, pyrite has originated in every way similar to kyanite. Crystals, in places with a chain-like distribution, form thin streaks one to two feet long. They apparently parallel the original bedding of the quartzite and similar chains of kyanite might possibly be seen if this mineral were more conspicuous.

ORIGIN OF THE KYANITE DEPOSITS.

The secondary origin of the disseminated kyanite is clearly indicated by its relation to the quartz of the host rock. Deposition by hydrothermal solutions is suggested by (1) quartz-kyanite veins cutting quartzite, (2) occurrence of seams of kyanite along contacts of schist and quartzite, (3) euhedral kyanite lining vugs in the quartzite, (4) smaller crystals of kyanite in the finer grained host rock, and (5) the association of pyrite with the kyanite. The solutions imported sulphur which combined with iron to form pyrite, and aluminium which united with silica to form kyanite metacrysts. The possibility that the aluminium may have been derived from the adjacent rocks deserves some consideration. The sericitic schist is believed to have been originally a more argillaceous sediment than the quartzite with which it is interbedded. Hydrothermal solutions circulating through it may have decomposed feldspars or minerals chemically similar, thus furnishing potassium for the sericite and aluminium for the kyanite. However, if such were the source of the aluminium, the schists should have a higher kyanite content than the quartzites since there is ample silica with which the aluminium could have combined. Furthermore, much of the schist high in sericite is lacking in kyanite. Apparently sericite formed independently of and probably before deposition of kyanite, although the paragenic relationship is not clear. The simplicity of the composition of the quartzite also argues against the formation of kyanite by mere recrystallization of an impure sandstone. If the sediment originally contained the aluminium then one would expect its metamorphic product to carry minerals in addition to quartz, kyanite, and pyrite.

It is concluded that both sulphur and aluminium were derived from a magmatic source and that the greater abundance of kyanite in the quartzite is due to the greater permeability of the latter. The permeability factor accounts for the seams of kyanite along contacts with less pervious schist, the smaller size and lesser amounts of crystals in the finer granular host, and the greater abundance in and around vugs as well as in the coarser quartzite.

If future quarrying discloses additional quartz-kyanite veins, the hydrothermal origin of the deposits will be further substantiated. Taber [5] figured a quartz vein from the Gold Belt in the James River Basin which contained

[5] Taber, Stephen, Geology of the gold belt in the James River basin, Va.: Virginia Geol. Survey Bull. 7, p. 128, 1913.

kyanite extending from the vein into wall rock. He also found fragments of veins on the surface containing tourmaline as well. Prindle [6] found kyanite in quartz veins which cut kyanitic quartzite at Graves Mountain, Georgia and concludes that the mineralization is of hydrothermal origin. Stuckey [7] has likewise argued for a magmatic source of solutions which have deposited kyanite. He says "formation of the cyanite deposits of North Carolina was by metasomatic replacement by hot solutions given off by the quartz veins, pegmatite dikes, and their parent magmas."

Whether kyanite rather than sillimanite was deposited appears to have been determined by the temperature of the solutions and the environment in which crystallization occurred. Elsewhere in the Piedmont of South Carolina, Smith [8] found sillimanite in schists that were intimately intruded by pegmatite. Mineralization here is in close proximity to intrusions, the most favorable places being in roof pendants in part surrounded by granite. Furcron and Teague [9] likewise noted that where sillimanite occurs, pegmatites are abundant and conversely in areas that contain kyanite pegmatites are few or absent. At Davy Mountain, Georgia, they found some specimens of sillimanite which have the structure and outward physical appearance of kyanite and concluded that the latter mineral was converted to sillimanite through the action of later, hotter pegmatite solutions. At Henry Knob the mineralizing solutions upon reaching the portion of the quartzite now exposed had certainly circulated a considerable distance from their origin and into an environment probably too low in temperature for the formation of sillimanite.

The most probable source of the hydrothermal solutions was from the magma which gave rise to the Yorkville granite. A large intrusion of this granite occurs a little over one mile to the south and others are exposed to the north and east of Henry Knob. Probably this granite is to be found at no great depth below the base of the knob. Consistent with the above discussion one might at first hand expect sillimanite to occur in the schist adjacent to this intrusion, but none has been found. However, this schist is largely a hornblendic metamorphosed intrusive, a rock in which sillimanite is probably not readily formed. Regional movements subsequent to mineralization account for the present distorted and fractured nature of some of the kyanite.

UNIVERSITY OF SOUTH CAROLINA,
COLUMBIA, SOUTH CAROLINA,
April 18, 1951.

[6] Prindle, Louis M., Kyanite and vermiculite deposits of Georgia: Georgia Geol. Survey Bull. 46, 1935.

[7] Stuckey, Jasper L., Origin of cyanite: ECON. GEOL., vol. 30, pp. 444–450, 1935.

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[9] Furcron, A. S., and Teague, Kefton H., Sillimanite and massive kyanite in Georgia: Georgia Geol. Survey Bull. 51, p. 29, 1945.

THE OCCURRENCE AND RELATIONSHIPS OF SOME MICA AND APATITE DEPOSITS IN SOUTHEASTERN ONTARIO.

J. B. CURRIE.

ABSTRACT.

The mica-apatite occurrences studied lie in North Burgess Township, Lanark County, Ontario. The rocks surrounding the deposits are dominantly crystalline paragneiss and limestone of the Grenville series. Their lithological variations stem from differences in the original composition of the sediments and the varying degree of metamorphism and injection by pegmatitic material which the rocks have undergone. Evidence is presented for the origin of the pyroxenite in the mica-apatite deposits through contact metamorphism of crystalline limestone by pegmatitic solutions. The close association of pyroxenite with mica and apatite in all the deposits examined suggests that pegmatitic solutions were responsible for the deposition of these minerals. Several lines of evidence support this view. Field and experimental information point to the sedimentary origin of the pink carbonate frequently found in the mica-apatite pits.

INTRODUCTION.

THE deposits of mica and apatite in the Precambrian rocks of Quebec and southeastern Ontario have been the subject of geological investigation over a period of more than eighty years. The dominance in size of the Quebec deposits over those in Ontario has led justifiably to a more intensive study of the deposits in the former region.

The mica-apatite occurrences studied lie in North Burgess Township, Lanark County, south of Perth townsite (Fig. 1). Field and laboratory work was directed toward a geological study of the area surrounding the deposits, the rocks associated immediately with them, and the genesis of the mica and apatite. An area of approximately four square miles west of Otty Lake was mapped on a scale of 1 inch to 500 feet and in order to determine that the relationships found there were general, a larger area was mapped on a less detailed scale (Map 1A).

GENERAL GEOLOGY.

General Features.—The rocks surrounding the mica-apatite deposits are dominantly crystalline paragneiss and limestone similiar to those which Logan classed as the Grenville series from his original mapping in Grenville Township, Quebec. In addition to regionally metamorphosed sediments, there are metamorphic pyroxenite and amphibolite, pink syenite of igneous origin, veined gneisses of mixed igneous and sedimentary derivation, and hybrid diorite, formed by the injection of pyroxenite by late pegmatite solutions. No evidence was observed of extrusive rocks or metamorphic schists that might have been derived from volcanic material.

The sedimentary rocks have been intensely deformed with resultant close-folding in the gneiss and plastic flow of the limestone. The complexity of stratigraphic relations caused by deformation precludes the arrangement of lithologic units on the basis of their relative age. The general strike of the structure is N40°E. The main northeast-trending folds are locally complicated by minor structures; for example the dome-like structure west of Otty Lake and the reversal of dips shown by the gneissic foliation on either side of the limestone band at the west shore of that lake. Field observation suggests that structural discrepancies noted between two given areas of gneiss, separated by limestone, may be explained by the incompetency of the latter. Thus, on a regional scale the pattern of structure is uniform, but locally notable irregularities are developed.

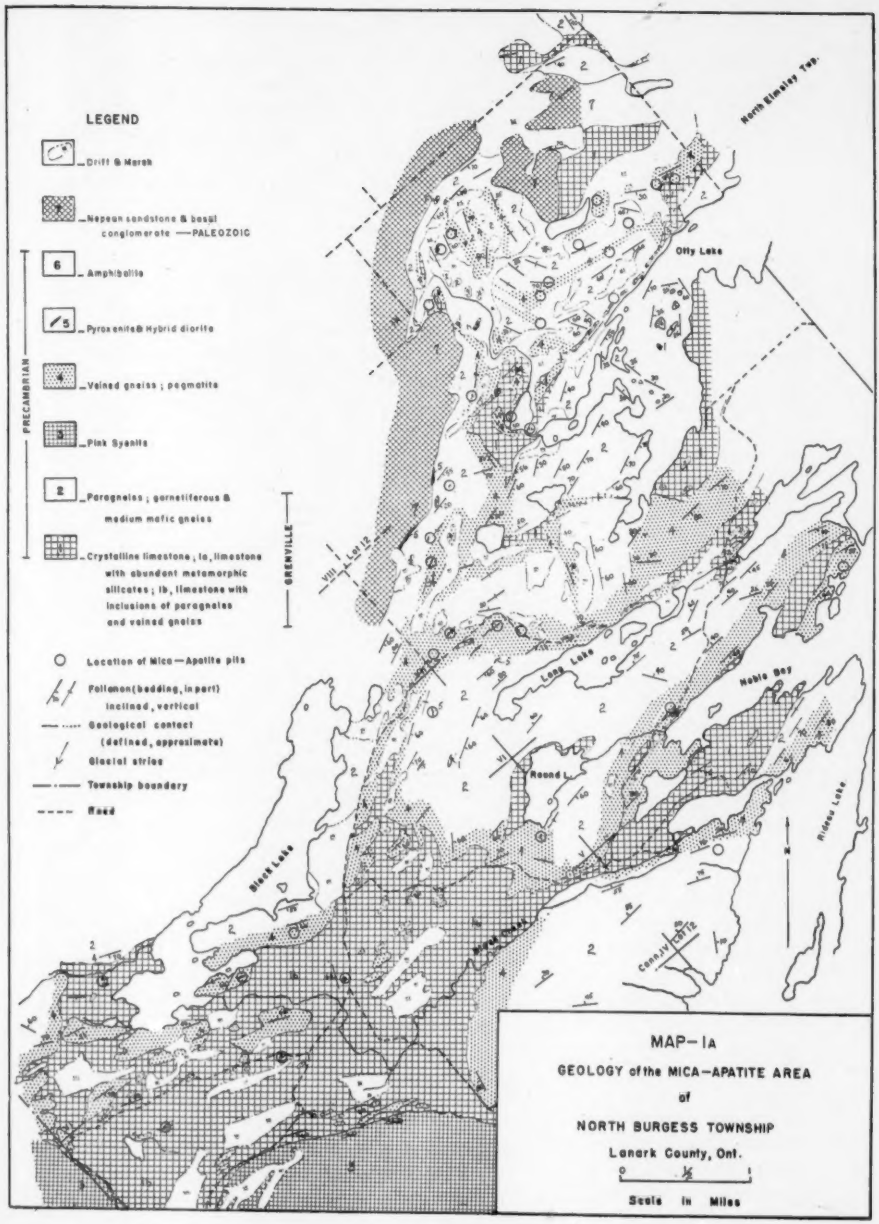
Pink syenite forms two roughly circular bodies at the southwest margin of N. Burgess Township. Amphibolite occurs on three islands in Otty Lake. Since these rocks bear no spatial or apparent genetic relationship to the mica-

FIG. 1.

apatite deposits in question, they need no further description. The petrology of the rocks associated directly with the deposits is discussed below.

The several lithological variations exhibited by rocks of the Grenville series stem from differences in the original composition of the sediments and the varying degree of metamorphism and injection by pegmatitic material which they have undergone. Field and laboratory investigation reveals that the sediments were of two main types; viz., clastic argillaceous beds and intercalated limestone with locally dolomitic facies. The gneissic rocks of the area have been produced by the metamorphism and injection of the clastic types by pegmatitic solutions while the chemical sediments have given rise to the coarsely crystalline limestone.

Limestone.—Limestone has reacted to deformation and metamorphism by recrystallization and plastic flow, expressed by three types of field occurrence. (1) Limestone that originally formed one continuous bed has been squeezed into lenses within the gneiss. The trace of the original bed is maintained by


LEGEND
Drift & Marsh
Nepean sandstone & basal conglomerate — PALEOZOIC
6 Amphibolite
5 Pyroxenite & Hybrid diorite
4 Veined gneiss ; pegmatite
3 Pink Syenite
2 Paragneiss ; garnetiferous & medium mafic gneiss
1 Crystalline limestone ; 1a, limestone with abundant metamorphic silicates ; 1b, limestone with inclusions of paragneiss and veined gneiss
PRECAMBRIAN
GRENVILLE
Location of Mica — Apatite pits
Foliation (bedding, in part) inclined, vertical
Geological contact (defined, approximate)
Glacial striae
Township boundary
Road
North Elmsley Twp.
Otty Lake
Long Lake
Round L.
Hobbs Bay
Pigeon Lake
Black Lake
Concession VIII
Lot 12
N
MAP—1A
GEOLOGY of the MICA—APATITE AREA
of
NORTH BURGESS TOWNSHIP
Lanark County, Ont.
0 ½ 1
Scale in Miles

a general alignment of the separated bodies. (2) In the course of intricate folding of the more competent gneiss, small bodies of limestone have become infolded in the gneiss or the gneiss has yielded to deformation by fracturing and small bodies of limestone have been injected into these openings. (3) In addition to the isolation of limestone within gneiss there are numerous examples of lenticular islands of the latter lying within the former. These bodies vary in length from a few inches to a thousand feet.

The crystalline limestone consists dominantly of large calcite grains (up to 10 mm) with minor amounts of serpentine, phlogopite and graphite. In thin section the carbonate is found to have irregular boundaries between grains. Phlogopite occurs as small flakes scattered throughout the calcite; frequently the grains are bent and calcite appears along the cleavage planes. Fine-grained serpentine, in matted aggregates, is usually present and may comprise 10 percent of the rock. Small grains of apatite are often associated with the silicates.

Thin limestone bands show a greater development of metamorphic silicates and locally approach a rock of pyroxenitic composition. The contact metamorphism of the limestone at contacts with gneiss or pegmatite will be treated in the following section.

Paragneiss.—The clastic sediments were injected by pegmatitic solutions through pores and along planes of discontinuity in the rock such as bedding and foliation. Rocks in which the injected material cannot be distinguished by eye from the host material are divided into garnetiferous gneiss and medium mafic gneiss. The latter represents the metamorphic derivative of a more dolomitic facies than the former.

Outcrops of garnetiferous gneiss form the main ridges of the area. The rock is medium grained and weathers brown to gray. On the weathered surface, the most conspicuous mineral is garnet which occurs as rounded grains up to 4 mm in diameter. Oriented mica flakes give the rock a gneissic texture. In thin section the garnet is seen to be commonly rimmed by biotite. The garnets are fractured, anhedral, and in many cases poikiloblastic with quartz near the center of grains. In most of the specimens examined microscopically, scattered prisms of sillimanite are oriented parallel to the foliation of the gneiss. Biotite varies from fine aggregates to large anhedral grains. Locally, fine-grained biotite occupies minute fractures transecting the rock. Magnetite and hematite appear as small grains along cleavage planes and marginal to the mica. In a few sections, biotite shows incipient alteration to chlorite. Anhedral grains of plagioclase (oligoclase-andesine, An 28 to An 36) vary in abundance from 5 to 15 percent of the rock. Corundum was observed in two sections in which quartz was subordinate or absent. It is associated with magnetite and the two minerals are surrounded by fine biotite.

The minerals just described occur as patches or bands surrounded by coarse-grained orthoclase-microperthite and quartz. These occurrences suggest that the aluminous minerals, sillimanite and corundum, were unstable in the presence of pegmatitic solutions. It is concluded that the original sediments were argillaceous and the present mineral assemblage is not the result of simple recrystallization of a clastic sediment but that these have been modified

by introduced solutions. Plagioclase generally forms a rim around patches of fine-grained sericite. In most sections it is impossible to determine the mineral from which the sericite is derived but in a few cases it appears to be a pre-existing plagioclase. Presumably, the sericite was formed by potash metasomatism during the main period of pegmatite injection. The plagioclase rims were probably formed by later alteration of the sericite by solutions carrying soda and acting interstitially to the potash feldspar grains. Additional evidence of these solutions is provided by the appearance of sodic plagioclase as vein perthite in the microcline of the veined gneiss and pegmatite. Cheng (3, p. 142) [1] has described a similiar occurrence from the Bettyhill Migmatite Area of Sutherland.

In the medium mafic gneiss the percentage of ferromagnesian minerals is consistently about 50 percent of the total constituents. These minerals include predominately hornblende and a diopsidic pyroxene from which the hornblende is in part derived. The feldspar is chiefly calcic oligoclase but antiperthitic intergrowths of sodic and potash feldspar are evident. Quartz is a variable constituent, usually present in quantities up to 10 or 20 percent. Accessory minerals in the medium mafic gneiss include sphene, apatite, chlorite and scapolite.

Veined Gneiss.—Veined gneiss is formed where injection of pegmatic material is visible as lit-par-lit veins along foliation planes in the gneiss. In cases of limited injection the intruded material is often sharply defined from the sediment but in the highly injected gneisses the distinction of pegmatite and host is less marked. Veined gneiss zones in paragneiss appear to be controlled by porosity and schistosity of the latter. That the fluid was injected along planes which were under compression rather than tension, is inferred from the irregular pinching and swelling of the pegmatite stringers. As pointed out by Osborne (10, p. 6), veined gneiss is often more prominently developed in the paragneiss at contacts of gneiss and limestone. This may be due to preferential injection of pegmatitic material into paragneiss in areas where the pressure consequent upon the intrusion was relieved by plastic flow in the adjacent limestone. The contact of gneiss and limestone being a plane of discontinuity and differential movement may also have offered an easier course of injection than foliation planes within the gneiss.

Pegmatites.—Within veined gneiss zones where injection was intensified or prolonged, the larger pegmatite bodies are formed and in many cases, coalescence of several small masses has led to the formation of a lenticular body of considerable size. The dikes usually cut the gneisses concordantly and in only two cases did the dikes show a transgressive relationship to the enclosing gneiss.

Mineralogically the pegmatites consist of microcline, perthite, plagioclase, quartz and minor amounts of biotite, carbonate and apatite. Potash feldspar is the most abundant constituent comprising normally 50 to 70 percent of the rock and locally rising above this amount. Microcline and perthite occur as large anhedral grains which show little or no alteration. The plagioclase (albite-oligoclase, An 10) is polysynthetically twinned, exhibits some sericitic

[1] Numbers in parentheses refer to Bibliography at end of paper.

alteration and occurs as small grains marginal to large microcline individuals, as large grains associated with microcline and as minute perthitic veins in microcline. Of the accessory minerals, biotite party altered to chlorite occurs as small interstitial grains marginal to microcline.

The pegmatites exhibit no chilled margins at their contact with country rock, nor is there evidence of mineral zoning within the bodies or systematic variation of grain size. None of the minerals found in complex pegmatites occur in these rocks.

Metamorphism.—In examining the rocks surrounding the mica-apatite deposits it is difficult to separate the mineral changes that are due to dynamothermal metamorphism from those due to contact metamorphism. In the gneiss, injection by pegmatitic fluids tends to replace the minerals formed at an early stage of metamorphism; viz., sillimanite, corundum, spinel, with those that are stable in the injected fluids. In limestone the chief effect of dynamothermal metamorphism has been the recrystallization of calcite and consequent coarsening of the grain. Deformation of the sedimentary rock during metamorphism supplied foliation planes in the clastic sediments and major planes of discontinuity at contacts of these rocks with limestone along which pegmatitic solutions entered the gneiss.

At all the contacts of limestone and gneiss examined some pyroxenitic rock is developed. It occurs as a coarse-grained rock of variable color ranging from nearly white to dark green. Diopside is the sole essential constituent of the pyroxenite and occurs as anhedral grains often in decussate texture. Minor amounts of phlogopite and apatite are often present; the former is poikiloblastic in, and marginal to diopside; the latter forms anhedral interstitial grains. These are the only minerals that occur with diopside in sections in which that mineral is unaltered.

Hornblende commonly occurs as replacement of the pyroxene forming large grains interstitial to, or surrounding it. Scapolite (mizzonite) is almost invariably associated with the hornblende as anhedral grains often partly altered to a fibrous form, presumably "wilsonite." The mica in these sections is almost entirely altered to greenish chlorite. Numerous interstitial grains of carbonate are present, especially in pyroxenite marginal to limestone bodies.

Evidence supporting the view that the pyroxenite has undergone alteration by late pegmatitic solutions, rich in soda, is afforded by thin sections showing the contact of pyroxenite and country gneiss. The latter had been injected by solutions which deposited quartz and oligoclase. Alteration of pyroxene to hornblende is visible around diopside grains and on approaching the quartz-rich rock the hornblende takes on the blue-green pleochroism of the sodic amphibole. A band of fine-grained scapolite is developed between the amphibolitized pyroxenite and the quartzose country rock.

Comparison of the contacts of limestone with feebly injected gneiss (paragneiss) and veined gneiss, respectively, illustrates the relative effectiveness of dynamothermal and contact metamorphism in the development of silicates in the limestone. At contacts of paragneiss and limestone only a narrow selvage of pyroxenitic rock is developed; whereas, at contacts of limestone with veined

gneiss or pegmatite, several feet of green pyroxenite may be formed. The contact of pyroxenite with limestone is well marked for the metamorphic rock gives way over a distance of a few inches to the recrystallized sediment. This restriction of contact metamorphic effects within narrow boundaries must be assigned to the ability of limestone to recrystallize and eliminate fractures and pore space at the prevailing temperatures and pressures.

In instances where the limestone was originally a thin lenticular body surrounded by gneiss and attacked by solutions moving through the latter, it has been converted entirely to pyroxenite or to pyroxenite enclosing mica and apatite and in some cases pink calcite which many investigators have viewed as of hydrothermal origin.

FIG. 2. Crystalline limestone intruding veined gneiss. West shore of Round Lake, North Burgess Township, Ontario.

The occurrence of the pyroxenite bodies within gneiss often at considerable distances from the nearest visible limestone outcrops and apparently unrelated to them, has led to the view that the pyroxenite is of igneous origin. It is noteworthy that geologists who have studied the pyroxenite while mapping the area surrounding the deposits in Quebec, both on a regional scale (19) and in detail (8) have concluded that the pyroxenite is a metamorphic rock. This origin of pyroxenite has been attacked on three points by the proponents of the igneous theory; namely, the transgressing relations exhibited locally by pyroxenite, chilled margins of the rock to country gneiss and pegmatite and the supposedly igneous origin of the pink carbonate.

These objections are open to question. The intrusive character of the crystalline limestone is frequently seen (Fig. 2) hence pyroxenite derived from it would probably show a transgressive relationship to the country rock.

No evidence of chilled margins was found where pyroxenite bordered other rock. Moorhouse (8, p. 33) records a similiar observation for the West Portland deposits of Quebec. Evidence supporting the view that the pink carbonate represents residual calcite (i.e., crystalline limestone) will be presented later.

The evidence pertinent to the origin of the pyroxenite is given here. (1) Pyroxenite occurring at the contact of limestone and gneiss or pegmatite is macroscopically and microscopically identical to that appearing completely within the gneiss. (2) Pyroxenite is present in larger volume where pegmatite is in contact with limestone than where paragneiss borders limestone. (2) Limestone at its contact with pyroxenite is often a pink color like that of the pink carbonate frequently present with pyroxenite in the mica-apatite pits. (4) In the majority of cases pyroxenite bodies parallel the enclosing rock and where cross-cutting relations were observed they are small offshoots of the main mass and traverse the gneiss for no great distance. These minor intrusions may have been formed by injection of plastic limestone, or limestone partly metamorphosed to pyroxenite, into the more brittle gneiss during deformation. (5) There is no evidence of the sharply-chilled margins between pyroxenite and gneiss or limestone as instanced by Spence (16, p. 40). The boundary between pegmatite and pyroxenite is often sharp but no change in grain size is seen on either side of the contact. (6) The pyroxenite bodies do not exhibit the usual form of dikes (i.e., strictly parallel walls continuing for some distance) but rather have a form similiar to the lenticular limestone bodies. (7) Pyroxenite exhibits no inclusions of paragneiss as might be expected if the rock were igneous and intrusive. (8) Drusy cavities found in the pyroxenite may well be due to the weathering out of residual carbonate and do not necessarily point to an igneous origin. (9) The typical minerals developed in the pyroxenite are those of contact metamorphic origin; diopside, scapolite, apatite and phlogopite. (10) The great variability of grain size and habit is not typical of igneous dikes. The frequent decussate texture is typical of metamorphic pyroxenite (5, p. 85). (11) The unmetamorphosed appearance of much of the limestone cannot be held as evidence against the contact metamorphic theory, as will be pointed out in the discussion of metamorphic temperatures. (12) No evidence was seen of exomorphic or endomorphic effects in thin sections of rocks bordering the pyroxenite.

Metamorphic Temperatures.—The temperatures and pressures at which the contact metamorphic rocks were formed is largely a matter of estimation. However, the question of the temperatures prevailing during the period of pegmatite injection, formation of pyroxenite and deposition of the mica and apatite, has been raised in connection with the deposits in Quebec (6, p. 385).

Buddington (1, p. 333) estimates that temperatures during regional metamorphism involving the Grenville series in the Adirondacks rose up to, and above, 600° C and that the depths at which metamorphism took place may have reached six miles or more in some localities.

Pyrite in specimens of pyroxenite from North Burgess was tested with the Pyrite Geo-thermometer (13) and gave as the average of 15 samples tested, two well-marked temperatures at approximately 475° C and 600° C. These two temperatures may indicate two periods of pyrite deposition or

they may be evidence that pyrite deposited at the higher temperature was reworked by late solutions at the lower temperature. Regardless of the significance attached to the lower temperature it is evident that some pyrite was deposited at the higher. Paragenetically the pyrite is later than the pyroxenite, thus temperatures during the early stages of metamorphism may have been in excess of 600° C. Since there is some doubt as to the significance of observations made with the geo-thermometer, it is interesting to note that comparable results were obtained by Peach (11, p. 36) in the case of some pegmatites from Hybla, Ontario.

Spencer (17, p. 91) has outlined probable crystallizing temperatures for various potash-soda feldspars and concludes that microperthitic orthoclase crystallizes within the temperature range of 950° C to 750° C. In the range from 750° C to 400° C the feldspar is mainly microcline-microperthite with some orthoclase-microperthite. The existence of both orthoclase- and microcline-microperthite in the gneisses and pegmatite surrounding the mica-apatite deposits points to metamorphic temperatures of the order of 750° C. Somewhat higher temperatures may have prevailed during the dynamothermal (regional) metamorphism and early in the period of pegmatite injection while the last pegmatite crystallization may have taken place somewhat below 500° C.

From field evidence it can be stated that the temperatures prevailing during regional metamorphism and probably during early contact metamorphism were sufficiently high to form garnet and sillimanite in the paragneiss. If temperature was the only factor controlling the degree of metamorphism undergone by the limestones they should show a greater abundance of metamorphic minerals throughout than they do. Instead, the limestone exhibits, for the most part, only recrystallization and coarsening of grain as the result of the high metamorphic temperature and pressure. Possibly the loss of fractures and porosity in the limestone prevented pegmatitic solutions from entering the main body of the rock and metamorphic effects are limited to its margin.

OCCURRENCE OF THE MICA-APATITE DEPOSITS.

Map 1A shows the distribution of the mica-apatite deposits and their occurrence within gneiss. Commonly the pits lie in gneiss which is, in turn, an inclusion in a larger limestone body. The map shows also that the deposits lie in gneiss marginal to limestone bands with the exception of the pits west of Otty Lake where this relationship is not apparent.

Mica and apatite of the deposits examined show certain consistent relations to each other and to the surrounding rocks. The minerals are invariably associated with pyroxenite and occur as pockets or lenses, vein-like masses or crystals in pink calcite. The spatial relationships of pegmatite, pyroxenite, mica, apatite and carbonate in the deposits examined are illustrated in Figure 3.

The deposits range in size from thin stringers of mica and apatite at the center of pyroxenite bodies to larger deposits fifteen feet wide and one hundred feet in length which have been mined to depths of seventy to eighty feet. The distinction between the pocket or lens and the vein deposits is

artificial for bodies which appear to be pockets may take on the aspect of a vein at a nearby point in the deposit. As noted by Spence (15, p. 117) the term "vein" for these occurrences is misleading "for the bodies are seldom continuous enough along their strike to be termed veins." It may be said that the pocket and lens deposits tend to be short in two dimensions and long in the third while the veins are narrow in width and of larger dimensions in length or depth. The dip of veins is variable even along the course of a single body; a change of dip from nearly vertical to almost horizontal within forty feet is recorded by Vennor (18, p. 118). Several occurrences of the pocket or lens type, noted by Vennor (18, p. 123), were exhausted at depths of a few feet.

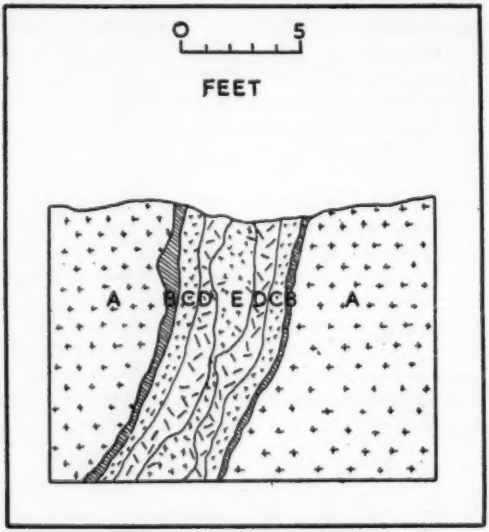


FIG. 3. Sectional view of mineral relationships in a mica-apatite deposit. A—veined gneiss or pegmatite; B—pyroxenite; C—mica; D—apatite; E—pink carbonate.

Mica is invariably present (not always in large quantities) between the pyroxenite and the apatite. At many pits apatite was deposited abundantly and mica was present in minor amounts while at others mica dominates and apatite may be almost absent. In some deposits the mica is crushed and twisted. Spence (15, p. 52) indicates that this condition often obtains when large quantities of phosphate are present but this habit was also observed at pits in which little apatite was developed.

Besides its occurrences as crystals, apatite in veins or lenses may have a massive or granular habit. The granular variety (sugar apatite) consists of

highly-fractured material suggesting that the granulation is due to deformation during deposition. A like opinion has been advanced for the twisted mica but evidence supporting this view is not conclusive. At some places veins of apatite and mica that bear cross-cutting relations to the pyroxenite are developed.

The common occurrence of pink calcite at the center of the deposits has been noted above and illustrated in Figure 3. From an examination of some phlogopite-apatite deposits of Quebec, Landes (6, p. 387) maintains that the carbonate was deposited from hydrothermal solutions while Moorhouse (8, p. 46) favors the view that the carbonate is residual and represents limestone recrystallized but not converted to silicates or phosphate. The several lines of evidence from the present study agree with the latter view.

Macroscopic and microscopic evidence favors a sedimentary origin. The pink or flesh color, characteristic of the calcite in the pits, is also seen in true limestone marginal to pyroxenite and grades outward from the latter to typical white limestone. The grain size of pink carbonate is frequently very coarse, but no more so than that of the limestone in many outcrops. From thin-section study, it may be said that the carbonate does not show any of the textures or structures typical of vein carbonate (4, p. 487), and differs little in this respect from the crystalline limestone. Crystals of calcite lining walls of a vug are infrequent and may easily be due to late solution and redeposition along fractures. The occurrence of rounded buttons of pink calcite completely enclosed by apatite crystals points to replacement of calcite by apatite.

Comparative spectrographic analyses were made to determine the relative abundances of trace constituents in samples of the pink carbonate and the limestone (Table I). It is apparent that while values shown for the elements in the carbonate may be above or below those recorded for the limestone, the order of magnitude shown for the seven elements in both the "vein" carbonate and limestone is very similiar. The pink color of the carbonate cannot be traced on the basis of these results to an increase in the abundance of some element over that in white calcite or limestone. Yet the color cannot be the result of photochemical changes for when salmon-colored carbonate is dissolved in hydrochloric acid the red color is present in the solution.

Since iron and manganese commonly give a yellowish or pink color to calcite (2) it is to be expected that one of these is active in the present case. The values for iron in Table I do not distinguish between ferrous and ferric iron. Thus, small amounts of magnetite in the limestone might be converted to hematite by reaction with carbon dioxide. Hematite occurs at several deposits as fine-grained masses.

The high ferric to ferrous iron concentration in limestone contact deposits has been often observed and has been ascribed by Lasky (7, p. 485) to the action of carbon dioxide on ferrous iron, or introduction of iron in the ferric state from an igneous source. Thus the consistently pink color of the carbonate is not necessarily indicative of an igneous origin but may indicate metamorphic action.

Rankama (12, p. 199) has outlined a theory according to which the heavy isotope of carbon (C^{13}) is concentrated by inorganic processes while organic

ones tend to accumulate the lighter isotope (C^{12}). Thus the ratio of C^{12}/C^{13} in chemically precipitated limestone is lower than that found in those rocks that are the products of organic growth. The ratio in carbon from meteorites lies between that of the inorganic and organic processes and is assumed to "actually show the primordial isotopic composition of the element" (12, p. 203.) The range of values of C^{12}/C^{13} ratios for carbon from sedimentary, igneous and meteoric rocks and minerals is shown in Table II. The range for igneous carbon overlaps that of carbon from sediments.

A determination of the C^{12}/C^{13} ratio was carried out for a sample of pink calcite from a mica-apatite pit and a sample of crystalline limestone from a band some one thousand feet from the pit. The ratio found is about three percent lower than the nearest value for the sedimentary carbon range given

TABLE I.

SPECTROGRAPHIC COMPARATIVE* ANALYSES OF CALCITE AND LIMESTONE.

Sample	% Mg	% Fe	% Al	% Sr	% Mn	% Cu	% Ag
C-1	.5	.6	.01	.2	.007	.0005	.0001
C-2	.7	.4	.005	.2	.004	.0005	.0001
C-3	.3	.2	.008	.06	.006	.001	.0005
C-4	.6	.4	.01	.2	.005	.0005	.0001
C-5	.3	.2	.01	.08	.006	.0005	.0001
C-6	.7	.7	.1	.1	.004	.0005	.0001

C-1, salmon-colored carbonate from pit south of Andrew Lake.
C-2, pink carbonate from pit south of Andrew Lake.
C-3, light pink carbonate from pit west of Long Lake.
C-4, pink carbonate at edge of 3″-calcite inclusion in pyroxenite.
C-5, white carbonate at center of 3″-calcite inclusion in pyroxenite.
C-6, limestone from band northwest of Long Lake.
* The figures are relative only and may be in error from the absolute value by a factor of 5.
J. E. Burgener—analyst.

by Rankama. In explanation of part of this discrepancy, Nier's statement (9, p. 647) "that the absolute values of such measurements may be in error by two percent due to systematic discriminations of the mass spectrometer," may be applicable. Regardless of errors in the absolute values, the relative values of the C^{12}/C^{13} ratio for the two samples agree to approximately 0.1 percent. This correspondence of values definitely favors a similiar origin for both samples.

Previous Opinions.—Although the Quebec deposits of mica and apatite have received more investigation than those of Ontario, many reports have pointed out the similarity in mode of occurrence and probable origin of the deposits in both regions. The origin of the apatite deposits in Ontario was, in early years, traced to sedimentary agencies. Apatite was said to occur as irregular beds running with the stratification of the gneiss and composed of nearly pure crystalline phosphate. This view was modified later when vein-like deposits were found which transgressed the bedding of the enclosing rock. The mineral was then held to be of dominantly sedimentary origin but with later modification by solutions to form the veining bodies. In ensuing years

the theory developed that the apatite and mica were entirely of igneous origin and that the adjacent rocks, i.e., gneiss and pyroxenite had derived part or all of their constituent material from a common deep-seated source. The view that the pyroxenite was intrusive and genetically related to the mica and apatite was advanced later by several workers. In recent years the contact-metamorphic origin of the pyroxenite by the action of pegmatitic solutions on limestone and the formation of apatite and mica by these solutions has been favored.

Origin of the Mica and Apatite.—Formation of the pyroxenite through contact metamorphism of limestone by pegmatitic solutions has been discussed in a preceding section. The close association of pyroxenite with mica and apatite in all the deposits examined suggests that pegmatitic solutions were responsible for the deposition of these minerals. In his discussion of the Quebec deposits, Landes (6, p. 388) maintains that the two minerals were deposited from a hydrothermal liquid derived from a "deeper crystallizing magma."

TABLE II.

C^{12}/C^{13} RATIOS.

	Type of material	Values of C^{12}/C^{13}
1	Meteoric carbon	89.5 to 92.0
2	Igneous carbon	89.0 to 90.2
3	Calcium carbonate from limestone	87.9 to 89.5
4	Pink calcite from North Burgess Twp.	84.90 (±0.1%)
5	Limestone from North Burgess Twp.	85.02 (±0.1%)

Values 1, 2 and 3 as given by Rankama (12, p. 204).
Values 4 and 5 from analysis by J. Macnamara, McMaster University, Hamilton, 1950.

A series of experiments at high temperature and pressure were devised, following the procedure of Smith (14, p. 535) to determine whether phosphorus would be concentrated in a pegmatitic solution, rich in silicates, or a hydrothermal solution, dominantly aqueous. Experimental results show that for a given amount of phosphorus, more than two-thirds of it would be partitioned into the silicate-rich fraction; hence, the pegmatitic fluids would carry the larger amount of phosphorus. Field observations and experimental data indicate that if both a pegmatitic and a hydrothermal stage are present, the former precedes the latter. Therefore, it is reasonable to suppose that phosphorus of the apatite was transported in the pegmatitic solutions.

Evidence that apatite was deposited from silicate solutions is found on examination of inclusions within the mineral. In addition to the usual solid inclusions of minerals such as phlogopite, there are minute cavities varying in size from 0.4 mm in length to several times that amount and suggesting, by their shape, a negative crystal of apatite. Within the cavities, minute acicular crystals have grown inward from the walls or radially from a core of opaque material in the interior. There is no sign of liquid within these cavities. Under the microscope the needle-like mineral shows low birefringence and an X-ray powder photograph gave a pattern identical to that of quartz plus a few lines of an unidentified material. Microscopic examination at very high power reveals small rounded inclusions which contain liquid and in some

cases solid material and appear to be of primary origin on the basis of their degree of filling and random disposition through the apatite. The occurrence of liquid in the small inclusions suggests that the larger ones which contain only crystals may have originally held liquid also, but fracturing of the apatite has allowed the fluid to escape.

As stated above, the phosphorus of apatite was carried probably by the pegmatitic solutions. That the water content of the solutions from which the phosphorus was deposited was higher than in the pegmatitic fluids that formed the pyroxenite, is indicated by the presence of liquid inclusions in the apatite. The present information suggests that apatite was deposited from solutions which were enriched in water during the late stages of pegmatite crystallization. The evidence does not support the transport and deposition of apatite from hydrothermal solutions not immediately related to the pegmatitic solutions in space and time.

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DISCUSSIONS

THE FORMATION OF LATE MAGMATIC OXIDE ORES.

Sir: In a paper published in this Journal ten years ago,[1] and in another, four years later,[2] I explained how, through the interaction of the forces of nature, as the earth cooled from a molten mass, the elements must have combined according to definite chemical laws and how the resulting compounds must have been disposed by gravity in concentric layers, increasing in density from the surface downward. It was shown that it is a rational concept that the heavy metals with their heavy oxides, sulphides, arsenides, selenides, and tellurides would sink below the silicate magmas, and remain there until forced up toward the surface through fractures in the solid crust. In the second paper I adduced evidence strongly indicative, if not conclusive, that the ores in hypogene deposits came up from deep-seated reservoirs, which underlie the heaviest, deepest, and most basic rock magma, rather than from discrete bodies of rock magma after it has been injected into a magma chamber. In other words, the evidence indicates that the abyssal theory of ore genesis is distinctly more rational than the magmatic theory.

If there has been any endeavor to disprove or discredit the evidence I adduced, it has not come to my attention, yet, there are those who remain loyal to their first love, even though they have to perform mental acrobatics to do so.

The magmatic theory is based upon the assumption that all the ores in deposits found in association with igneous intrusions, came up more or less evenly mixed with the rock magma, and were dissociated from the magma as it cooled and were segregated into comparatively pure concentrations. This assumption, it seems to me, is wholly unrealistic. It is a reasonable conception that the silicate magma and the ore would have been separated by gravity while in repose before they were thrust into the magma chamber; probably along contacts there would be some admixture. When cracks in the crust penetrate to the underlying magma, the fluid in the uppermost and lightest zone would be ejected first, followed by the contents of the deeper and denser zones, that is, (1) silicates, by far the largest deposits of intrusives, (2) possibly a mixture of basic silicates and oxides, and (3) heavy-metal ores. If the oxides—magnetite, ilmenite, and chromite—come with the magma, they settle out in deposits conformable with the enclosing rock, truly magmatic deposits, but usually small and inconsequential.

Now, it has been proved that the ores in many of the so-called magmatic deposits transgress the structure of the enclosing rock and also that of any pre-

[1] White, C. H., A theory for the concentration and distribution of copper in the earth's crust: ECON. GEOL., vol. 36, pp. 1–18, 1941.

[2] White, C. H., The abyssal versus the magmatic theory of ore genesis: ECON. GEOL., vol. 40, pp. 336–344, 1945.

existing ore bodies. The repeated invasions of fluid ores or ore-bearing fluids is of frequent occurrence in many mining districts, and is simply and rationally accounted for by the abyssal theory of origin, but such occurrences present, what would appear, insurmountable difficulties to adherents of the magmatic theory. However, Alan M. Bateman, in a recent paper,[3] attempts to solve the problem by conceiving a new process of differentiation and concentration which he calls "Late Gravitative Liquid Accumulation." After describing the process, he tests its validity against occurrences heretofore considered typically magmatic. It is not my purpose to criticize his theory, but I wish to point out that in every case cited, the existing conditions can be better and more simply accounted for by the abyssal theory.

The Palisades of the Hudson River is a horizontal sill of basic igneous rock nearly 1,000 feet thick with an olivine-rich zone near the base, "above which lies a zone richer in basic pyroxenes," while in the upper third of the section "titaniferous iron ore is sufficiently abundant to be a major constituent." That is, the lighter magma came in first, followed by the intermediate, and, finally, by the heaviest; the order in which, according to the abyssal theory, they would have been released.

In the Adirondack titaniferous magnetite deposits, the sequence of injections was, apparently, the same as at the Palisades; first the lighter anorthosite, followed by gabbro and ore, with two invasions of ore. The first, structurally in accordance with the anorthosite, the second, traversing earlier structures, in accordance with the theory of deeper than crust origin. And the ores in the Bushveld igneous complex, chromite and magnetite, are in the same relative position; that is, the lighter chromite is far below the magnetite.

The platinum pipes in the Bushveld igneous complex are perfect examples of deposits of abyssal origin. These pipes—some 60 are known—come up through norite. They are from 600 to 800 feet in diameter; the outer cylinder next the norite is pyroxene, within which is a cylinder of olivine dunite holding a central core 60 feet in diameter consisting of "hortonolite dunite with magnetite, ilmenite, chromite, and minor sulphides carrying platinum." The cylinders increase in basicity and density toward the center, which carries platinum, the least exothermic of the metals; just the order in which these minerals would be concentrated below the crust, and the order in which, according to the abyssal theory, they would be ejected up through the crust.

The titaniferous iron ore of Taberg, Sweden, injected into intrusions of hyperite and anorthosite, and carrying specks of pyrrhotite, pentlandite, chalcopyrite, and pyrite, suggests that the ore came in after the intrusion of the silicates from the transition zone in the magma between the oxides and sulphides.

The large bodies of ilmenite ore at Lake Allard, Quebec, in immense masses of coarse anorthosite, showing intrusive relations to the anorthosite, with dikelets of coarse granular ilmenite extending out into the anorthosite, are perfect examples of later intrusions into the host rock; moreover, there is

[3] Bateman, Alan M., The formation of late magmatic oxide ores: ECON. GEOL., vol. 46, pp. 404–426, 1951.

no evidence that the ore was mixed with the anorthosite after they entered the magma chamber. And since, through the action of the forces of nature according to established natural law, the ore and the rock magma would have become differentiated before they started on their journey up to the magma chamber, it seems unnecessary to try to invent a less rational concept of origin.

One could not hope to find a better example of a deposit of abyssal origin than the great magnetite deposit at Kiruna, Sweden. J. H. L. Vogt, Lindgren, and Geijer agree that the magnetite is without doubt an injection into the adjacent syenite, but their allegiance to the magmatic theory impelled them to postulate, it seems to me gratuitously, that the ore was differentiated from the syenite, and later, by devious ways, was injected back into it again, though there is no evidence that the ore was ever mixed with the rock magma in the magma chamber.

In the second paper referred to above I have shown that the abyssal theory of ore genesis has a more rational scientific foundation than has the magmatic theory, and that, as a guide in the search for ores, it is more reliable; now, that the heretofore best representatives of the magmatic theory are found to be even better representatives of the abyssal theory, it appears incontestable that magmatic differentiation within the magma chamber plays a very minor role in the formation of ore deposits.

CHARLES HENRY WHITE.

3440 CLAY STREET,
SAN FRANCISCO, CALIF.,
July 31, 1951.

REVIEWS

Application of Geology to Engineering Practice—Berkey Volume. Pp. 327; figs. 60; pls. 27. SIDNEY PAIGE, Committee Chairman. Thirteen papers by eighteen authors. The Geological Society of America, New York, 1950. Price, $2.75.

This Special Volume of the Geological Society of America was issued to honor Dr. Charles P. Berkey, for eighteen years the able Secretary of the Society and its President in 1941. It consists of twelve papers dealing with various phases of Engineering Geology, a field in which Dr. Berkey, Newberry Professor Emeritus of Columbia University, has been regarded by both geologists and engineers as pre-eminent. The book was prepared under the supervision of a committee headed during the earlier stages by Dr. W. O. Hotchkiss and later by Dr. Sidney Paige.

Following an Introduction by Dr. Paige setting forth the nature of Engineering Geology and its place in the science and technology of the modern world a first chapter in the book discusses Dr. Berkey's professional work and some of his accomplishments. It is by two men who have had many contacts with him on engineering projects, John L. Savage and Roger Rhoades.

Then Edward B. Burwell, Jr., and George D. Roberts, in a paper entitled "The Geologist in the Engineering Organization," take up the qualifications of an engineering geologist and his functions and responsibilities.

In the first part of the next section on Geology in Dam Construction Burwell treats the subject of exploration, testing of materials and problems relating to dam sites located in a number of different types of rocks. In the second part Berlen C. Moneymaker deals with dam sites in intrusive igneous rocks, limestones, and metamorphic rocks, discussing examples of each.

The effect of geological conditions on the design and construction of tunnels is discussed by the late James F. Sanborn, with numerous illustrative cases.

Karl Terzaghi, in Mechanism of Landslides, treats briefly the varieties of slope movements, the processes leading to landslides, their dynamics, and preventive and remedial measures, citing ground displacements in different parts of the world.

Faults and Engineering Geology, by George D. Louderback, is a comprehensive discussion of fault movements, their effects on the rocks in the fault zones, and how these phenomena introduce problems at the sites of dams and certain other engineering structures. Active faults and their consequences are treated separately. Illustrative examples of engineering projects rendered more difficult by each type of fault are cited.

Groundwater Geology is sometimes set off as a distinct field from Engineering Geology, but the Berkey Volume includes a rather complete statement by the late Oscar E. Meinzer on the occurrence and development of underground water and on the control of water in other engineering projects.

Geologists have worked with highway engineers for a longer period—at least some 50 years—than with most other branches of engineering, and some of the current problems are discussed by E. F. Bean in a brief section. He treats the influence of geological conditions on location, design and construction, and also indicates the nature of the search for roadbuilding materials.

Under the caption of Geological Aspects of Beach Engineering W. C. Krumbein takes up shoreline processes and the nature and results of shore-protective structures.

The deterioration of concrete through chemical reaction between cement and aggregate has become a very serious problem in many large structures in recent years and much research has been done to determine the cause or causes. The problem is partly petrological, in connection with the mineralogical composition of part of the aggregate used; partly chemical, relative to the composition of the cement, especially as to alkali content, and the reactions involved; perhaps partly engineering, through the effect of the climatic and moisture conditions to which the finished structure is subjected. A chapter by Duncan McConnell, Richard C. Mielenz, William Y. Holland, and Kenneth T. Greene summarizes research on the petrology of aggregates, chemical reaction, and the mechanism of the deterioration.

Petroleum Geology has customarily been considered to be a field coordinate with Engineering Geology but K. C. Heald, in a section headed Geologic Engineering in the Petroleum Industry, has demonstrated the variety of ways in which Geology is utilized, not merely in the search for petroleum, but in connection with drilling and completing wells, guiding oil field development, transportation, and the securing of maximum recovery.

Mining Geology is in part a science but also is related to Engineering Geology in that boundaries and quantities of ore are determined and excavation and exploitation are directed. Murl H. Gidel has contributed a chapter entitled Geology in the Discovery, Development, and Exploitation of Mineral Deposits, in which some of the topics discussed are the structure and origin of mineral bodies in different host rocks, the surface indication of ore deposits, and the use of geologic principles in the examination of mining prospects and in guiding mine operations.

The volume closes with a section on Military Geology by Charles B. Hunt. The various ways in which geologic information is highly valuable for military operations are outlined with illustrations, and the organization of the Military Geology Unit is discussed with reference to purpose and functions and both strategic and tactical intelligence.

The authors of the different chapters of this book, all specialists in their respective fields, have contributed highly instructive, interesting, and very readable brief accounts of some of the branches of Engineering Geology. They have produced an excellent volume of value also to geologists working mainly in other divisions of the subject and to students who wish to gain some knowledge of geology applied to engineering. Application of Geology to Engineering Practice serves fittingly and happily to honor Dr. Charles P. Berkey.

JOHN P. BUWALDA.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA 4, CALIFORNIA,
July 24, 1951.

Mica Deposits in Minas Gerais, Brazil. By W. T. PECORA, M. R. KLEPPER, D. M. LARRABEE, A. L. M. BARBOSA, AND RESK FRAYHA. Pp. 100; figs. 33; pls. 4; tbls. 8. U. S. Geol. Survey Bull. 964-C, 1950. Price, $0.60.

Pegmatite Investigations in Colorado, Wyoming, and Utah, 1942-1944. By J. B. HANLEY, E. W. HEINRICH, AND L. R. PAGE. Pp. 125; figs. 34; pls. 17; tbls. 7. U. S. Geol. Survey Prof. Paper 227, 1950. Price, $1.50.

Mica and Beryl Pegmatites in Idaho and Montana. By W. C. STOLL. Pp. 64; figs. 25; pls. 9; tbls. 25. U. S. Geol. Survey Prof. Paper 229, 1950. Price, $1.50.

These three publications, all issued during the past year, are outgrowths of pegmatite-mineral investigations made in Brazil and the United States by the Geological Survey during the period of World War II. Summaries of similar

investigations in several other parts of the United States already have been issued or are in process of publication.

Based as they are upon comprehensive and detailed field studies of hundreds of pegmatite deposits, many of which were unusually well exposed as a result of wartime mining operations, these three reports are authoritative contributions to the structural and economic geology of such deposits. The reader will be impressed with their wealth of descriptive detail, including numerous maps and diagrams, and he assuredly will appreciate the authors' attempts to derive meaningful generalizations from substantial accumulations of structural and petrologic data. He will be disappointed, however, if he anticipates extensive discussions and analyses of such features as detailed mineralogy, mineral genesis, and pegmatite geochemistry. The reports are frankly economic in scope, and hence deal primarily with features of direct or indirect application to prospecting, development, or mining.

The report on Brazilian mica deposits is an exceptionally well balanced summary of a large and rather complicated subject. It comprises data and discussions in the fields of mineral economics, general geology, pegmatite geology, mineralogy, mining techniques, and mineral preparation as they relate to the production of mica and associated minerals. Of particular interest and clarity are the section on geology of the mica-bearing pegmatites and the section in which the structural features and other properties of commercial mica are described. Analyses of mine-run and sheet mica production are presented in some detail, and should prove especially useful during any future period when considerable increases in the output of Brazilian muscovite are required.

The two reports on deposits of mica, beryl, and other pegmatite minerals in Colorado, Wyoming, Utah, Idaho, and Montana follow a somewhat different pattern. They present general discussions of pegmatite geology, mineralogy, and mineral economics in more abbreviated form, but on the other hand, they include detailed descriptions of the many deposits that were examined. These descriptions, which constitute the bulk of both reports, effectively illustrate and document the generalizations made with respect to the geology of pegmatites, and of course are of immediate value to persons concerned with individual deposits.

Some readers probably will be dissatisfied with the very brief discussions of geologic features and origin of pegmatites in the Idaho and Montana districts. Although one is stimulated, for example, by such statements as those concerning the differences between "rum" and "green" micas and the differences between their associated minerals in the Avon district of Idaho, he remains uninformed as to the specific nature, distribution, and possible significance of these differences. Much more satisfactory in this respect is the report that deals chiefly with the Colorado pegmatites. In addition to readily understandable descriptions and summaries of pegmatite structure and types of pegmatite-mineral deposits, for example, the authors have provided brief but thoughtful discussions on the origin of such features. They have been careful to outline alternative hypotheses concerning such controversial questions as the genesis of pegmatite bodies with complex internal structure, and have presented arguments and lines of evidence in a refreshingly objective manner.

These three reports are valuable additions to the voluminous literature on pegmatites, in large part because they contribute such a wealth of information on the structure of pegmatite bodies and pegmatite deposits. This information is of both economic and scientific interest. The vast majority of the described pegmatites consist of two or more lithologic units—each distinguishable on the basis of mineralogy, texture, or both features—that occur as successive shells and tend to re-

flect the shape of the enclosing pegmatite body. These are termed zones, and in some bodies they are transected, corroded, or extensively replaced by masses of younger pegmatite material.

Despite minor differences of terminology used by the various authors, one is impressed with the fundamentally similar petrology and internal structure of commercially important pegmatites in such widely separated areas. As observed from the walls inward to their centers, individual pegmatite bodies show remarkably similar textural variations and sequences of mineral assemblages from one district to another. Such an essentially orderly or systematic disposition of minerals within a pegmatite, though denied—by implication or even directly—by many previous investigators, seems to have been clearly established through these and other recent studies. The economic value of such detailed examination of mineral occurrence is evident, in terms of both exploration and development of deposits.

In summarizing their views on the origin of zonal structure, Hanley, Heinrich, and Page conclude that it is developed by fractional crystallization in place, with incomplete reaction between crystals and the rest-liquid. Hypotheses of channel filling by hydrothermal solutions, and of magmatic crystallization followed by open-system replacement, are tentatively rejected, owing chiefly to the discrete, lens-like form of most pegmatite bodies, and to the consistent increase in age of the zones from the core to the walls of a given body. They evidently favor explanation of most observed replacement relations as results of reactions between earlier-formed (zonal) minerals and rest-liquids. This is at interesting variance with the views of several earlier students of pegmatite geology and mineralogy.

These publications are admirable complements to the many papers and reports on pegmatite mineralogy published during the past seventy years. They represent a mode of detailed study that has long been applied to ore deposits with considerable success, and they provide a much firmer basis for further critical work on the always-fascinating problems of pegmatite genesis.

RICHARD H. JAHNS.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIF.,
July 24, 1951.

Die Erzmineralien und ihre Verwachsungen. BY PAUL RAMDOHR. Pp. xvi + 827; figs. 431; numerous tables. Akademie-Verlag, Berlin, 1950. Price, D.M. 93.00 bound, D.M. 88.00 paper-covered.

This comprehensive volume which may perhaps best be translated as "the ore-minerals and their intergrowths" is a valuable addition to the number of eminent books that have already been published on this subject. The author, who is professor of mineralogy at the Humboldt University in Berlin, is best known to the economic geologist for his co-authorship with Schneiderhöhn in the "Lehrbuch der Erzmikroskopie." This book appeared in its second edition in 1931 and has been out of print for many years; many copies were destroyed during the war. The present volume therefore fills a longfelt need. It was originally intended as a new edition of the combined work of the two authors, but Schneiderhöhn was preoccupied with other work and Ramdohr took on the sole authorship.

A detailed discussion of textures, structures, and the intergrowths of several ore-minerals and their genetic interpretation, not covered in the Lehrbuch, has been included in the present volume. The present volume should be considered a Handbuch rather than a Lehrbuch (textbook)!

The book is divided into two parts. The first part deals with the intergrowths of the ore-minerals and the second discusses their properties. A genetic classification of ore deposits introduces the first part and includes discussions of the genesis of ore minerals associated with igneous, sedimentary and metamorphic processes. This study embraces 51 pages and is rather detailed for a book about polished surface studies. The discussion of metamorphic processes is particularly emphasized and follows the European school of Grubenmann and others, "pigeonholing" the respective relevant ores into kata, meso and epizones. Painstaking compilations of data are manifold and are neatly arranged in tables.

About 100 pages are devoted to descriptive accounts of the intergrowths of the ore-minerals. Textures, reaction rims, inclusions, criteria for the recognition of replacement phenomena, myrmekitic intergrowths, relict-textures, zoning and twinning are examples of subjects discussed. The descriptions are detailed, abundantly illustrated and supplemented by tables. The table following the discussion of unmixing quotes 120 examples. A space is left for the reader headed "for further additions and new examples"!

The major part of the book covers descriptions of the individual ore-minerals. Their properties in reflected light are discussed, both as studied with air and oil immersion objectives. Etch patterns, chemical properties, textures, intergrowths, distribution and occurrence, and X-ray powder patterns are also described. A bibliography is given at the end of the description of each mineral. Photomicrographs and drawings illustrate the more important points.

An exhaustive bibliography citing more than 800 references follows the descriptive part of the book. In addition to the German references, American geological journals, particularly Economic Geology, feature prominently among those listed. Surprisingly, few Russian references were included, despite the high degree of achievement of the Russians in this science.

The last chapter is a compilation of the major ore occurrences in the world. It notes the names of the localities, and their types of mineralization. Although this list covers 17 pages it could be appreciably extended. Such well-known mining camps as Santa Rita, Ajo, Coeur d'Alene and Boulder, to name but a few, have been overlooked entirely. Vredenburgite, jacobsite and graphite were listed among the ore-minerals of Franklin, New Jersey; willemite, however, was not listed. In fact, willemite was entirely omitted from the book, however many silicates were included.

The book is competently written and exceptionally well illustrated. It is an up-to-date, useful reference, and one of the most comprehensive on the subject. The author is to be congratulated for the degree of excellence of his book.

GERALD M. FRIEDMAN.

UNIVERSITY OF CINCINNATI,
CINCINNATI, OHIO,
July 10, 1951.

Diccionario Minero-Metalúrgico-Geológico-Mineralógico-Petrográfico y de Petróleo: Ingles, Español, Francés, Alemán, Ruso. BY ALEJANDRO NOVITZKY. Pp. 369. Buenos Aires, Argentina, 1951. Price, 120 Argentine pesos.

The author has almost 20 years of experience in mines and worked in some of the most important metal and coal mines and oil fields of Europe; he studied and worked in France, Yugoslavia, Bulgaria, Austria, Germany, and is now in Argentina. He has published a French-Russian mining, metallurgical and geo-

logical dictionary, and collaborated on a German-Russian dictionary on petroleum terminology.

Anybody who has to handle a lot of foreign publications on geology would be delighted at the news of a new five-language dictionary. However, the first look at this dictionary provides the first deception: it is very big and bulky, $9\frac{1}{2} \times 13''$, not an easy size to handle when you are in a hurry to find the translation to scientific words. The paper cover is not good protection for a book that supposedly is to be used very often. And upon studying the contents of the dictionary we were further disappointed; the fact that it is a one-way dictionary, with the English word given alphabetically, then its Spanish, French, German, and Russian translation, makes it rather useless for those who live in English-speaking countries. We could only use it once in a great while, when a foreign geologist is visiting us and we want to convey a word in his language. What we need is to know in English what a foreign author is talking about. We can see, though, how this dictionary could have some use for foreign geologists who in their country receive English publications and want to know what it means in their language, and also for geologists of English-speaking countries who are working or visiting outside their country and want to convey to their listeners a term which they only know in English. As for the column of Russian words, it is of doubtful value, except to those who are familiar with the Russian alphabet.

Of course there are quite a few geological terms which are similar in the various languages, or at least with the same root, but those are the words which we would not need to look up, except for spelling; it would require too much time to try and find words by analogy. We realize, however, that a key language had to be chosen, in this case English, because to make it a five-way dictionary with the first alphabetical list in each one of the languages would make it much too bulky.

Although it cannot compete with a two-way dictionary for one language, the book represents an important effort and will be profitably used by many scientists and scholars.

M. L. MIGNONE.

Principles of Petroleum Geology. By WILLIAM L. RUSSELL. Pp. 508; figs. 132; tbls. 9. McGraw-Hill Book Company, Inc., New York, 1951. Price, $7.00.

This latest textbook on petroleum geology by Russell follows closely on Kenneth Landes' *Petroleum Geology* and follows quite a different arrangement from that of Landes or Lalicker's still earlier *Principles of Petroleum Geology*.

This volume is both a textbook and general reference on the subject. It gives discussions of principles, methods, and techniques and omits long detailed descriptions of oil fields and their stratigraphy. In addition to the customary treatment of origin, accumulation of oil, and various oil traps, it emphasizes geophysics and, as would be expected from the author's work, well logging methods and their interpretation. The gamma ray and neutron well logging is given for the first time. The book throughout emphasizes the practical application of principles and characteristics of oil and gas fields that would aid in their discovery are pointed out.

The 29 chapter headings are repeated here to give an idea of their contents: The Science of Petroleum Geology; Subjects Related to Petroleum Geology; Chemistry of Natural Hydrocarbons; Physical Properties of Petroleum; Oil-field Waters; Methods of Representing Geological Conditions; Structures Important in Petroleum Geology; Reservoir Rocks; Classification of Traps for Oil and Gas Accumulation; Subsurface Pressures; The Origin of Petroleum; The Migration

and Accumulation of Oil and Gas; Regional Alteration and Its Relation to Oil and Gas Production; Relations of Oil and Gas Fields to Unconformities; Depositional Features; Surface Indications; Salt Domes; Lithologic Well Logs; Electrical Well Logs; Radioactivity and Neutron Well Logs; The Correlation of Well Logs; The Use of Geochemistry in the Search for Oil and Gas; Magnetic, Gravimetric, and Electrical Geophysical Methods; Geophysics—Seismic Methods; The Development of Oil and Gas Fields after Discovery; Summary of Methods of Locating Stratigraphic Traps; The Search for Oil in the Continental Shelf; Exploration for Oil and Gas and the Appraisal of Prospects; The Future of Petroleum Geology.

Abundant footnotes carry references to the literature and some chapters have additional lists of selected references. The illustrations are fairly numerous and well selected. The author has been thorough in his treatment of the various phases of the subject.

This volume will probably prove to be the most widely used of all textbooks on petroleum geology.

The Conservation of Ground Water—A Survey of the Present Ground-Water Situation in the United States. By HAROLD E. THOMAS. Pp. 327; figs. 3; pls. 3. McGraw-Hill Book Co., Inc., New York, 1951. Price, $5.00.

This book is gotten out under the auspices of the Conservation Foundation, which "was established in 1948 as an independent non-political organization to investigate facts and to educate. It is dedicated to the conservation of the earth's life-supporting resources." It can be welcomed as the first of its kind published in the United States. It surveys the natural conditions determining ground water and treats of the history and effects of the use of ground water throughout the country, surveying all the developments. It provides a discussion of the natural and legal factors involved in ground water development and use in the United States.

The book deals first with basic hydrologic data and principles and gives an inventory of the United States total water resources. It then deals with the information accumulated in 70 different areas in the development of the ground water and the problems that arose and the methods used to cope with them. It also covers overdraft, depletion, salt-water intrusion, and management practices.

Fairfield Osborn, President of the Conservation Foundation, points out in a foreword that we are face to face with problems of inadequate water supply, or unsatisfactory quality, or both and that while the population has doubled in the last 50 years the per capita consumption of water has also increased greatly. The author states in his preface that the use of ground water in agriculture and industry had by 1945 increased by about twice what it had been ten years before. Such a book is, therefore, timely and welcome.

The chapter headings are: Introduction; Hydrologic Principles and Basic Data; Problems Resulting from Ground-Water Development and Use; Ground-Water Problems Resulting from Land Occupancy; Our Increasing Requirements for Water; Current Deficiencies and Future Needs for Effective Ground-Water Development; Better Ground-Water Management.

The coverage of the individual chapters is very thorough and Appendix II gives 21 pages of references to the bibliography arranged according to areas that yield problems of ground water. As a member of the U. S. Geological Survey, the author is well qualified to bring together and analyze the large amount of data relating to this important subject. The book will prove of value to geologists,

hydrologists, engineers, and the interested layman. The author, the Conservation Foundation, and McGraw-Hill Book Company are to be congratulated for bringing out such a fine piece of work.

Climate in Everyday Life. By C. E. P. BROOKS. Pp. 314; figs. 34; tbls. 26. Philosophical Library, New York, 1951. Price, $4.75.

The jacket of this interestingly written book carries the following: "The more changeable a climate is the more it occupies us. The purpose of this book is to assist the reader to make the best of the climate in which he lives. . . . The effects of climate on customers' needs and on conditions of transport and storage make up important information for the business man." These succinct phrases summarize the theme of the book. In Part I, "Living with the Climate," the types of climate are given and the effects of climate on services and architecture. Part II, "Climate as an Enemy," deals with the effect of heat and humidity, on goods, smoke, and climatic accidents. Part III, "The Control of Climate," deals with heating, air conditioning and clothing.

It is nicely written in simple language that all can enjoy.

BOOKS RECEIVED.

DONALD H. KUPFER.

Tenth Semiannual Report of the Atomic Energy Commission. GORDON DEAN, Chairman, ET AL. Pp. 151. U. S. Government Printing Office, Washington, D. C., July 1951. *Review of activities for first half of 1951.*

California Division of Mines—San Francisco, May–September 1951.

Special Rept. 7–B. Economic Geology of the Rincon Pegmatites, San Diego County, California. JOHN B. HANLEY. Pp. 24; figs. 5; pl. 1. Price, 35 cts. *Description of the structure of the pegmatites, origin by intrusion and crystallization. Brief description of individual mines and prospects.*

Special Rept. 10–A. Nephrite Jade and Associated Rocks of the Cape San Martin Region, Monterey County, California. RICHARD A. CRIPPEN, JR. Pp. 14; figs. 14. Price, 25 cts. *Review of U. S. occurrences and geology of the Monterey deposits. Origin ascribed to chemical reconstitution of cataclastic rocks under rotational stress.*

Special Rept. 10–B. Nephrite in Marin County, California. CHARLES W. CHESTERMAN. Pp. 10; figs. 16. Price, 25 cts. *Describes geology of the deposit. The nephrite was deposited along shear zones from solutions derived from serpentine.*

Special Rept. 10–C. Jadeite of San Benito County, California. H. S. YODER AND C. W. CHESTERMAN. Pp. 8; figs. 6. Price, 25 cts. *Describes geology of the deposit with origin ascribed to syntectonic deposition of jadeite from residual fluids of the process of serpentine formation.*

Special Rept. 11. Guide to the Geology of Pfeiffer Big Sur State Park, Monterey County, California. GORDON B. OAKESHOTT. Pp. 16; figs. 28; pl. 1. Price, 25 cts. *Technical report; the Sur complex is thrust over the Franciscan rocks; well illustrated.*

Colorado School of Mines Quarterly—Golden, January–April, 1951.

Vol. 46, No. 1. An Introduction to the Design of Underground Openings for Defense. Compiled by CLIFTON W. LIVINGSTON; edited by LEROY W. GOODWIN. Pp. 304; figs. 118; pl. 1; tbls. 22. Price, $3.00. *A comprehensive report on the progress to date, consisting of the following articles: Protective Standards for Underground Defense, by Edmond H. Leavey, Jr.; The Mechanics of Rock Failure, by John P. Cogan; A Review of Rock Pressure Problems, by Richard V. Shoemaker; A Method for the Determination of Stresses Around an Opening Under Impact Loads, by George E. Hesselbacher, Jr.; Rock Tunneling for Underground Protective Construction, by Bruce D. Jones; Heating, Ventilating and Air Conditioning of Underground Installations, by Irvin Marshall Rice.*

Vol. 46, No. 2. An Introduction to the Study of Organic Limestones. J. HARLAN JOHNSON. Pp. 185; fig. 1; pls. 104. Price, $2.00. *Ten groups of organisms are considered as to physical and chemical form of the material being preserved: foraminifera, poriferasponges, coelenterata, echinoderma, bryozoa, worms and worm limestones, brachiopoda, mollusca, arthropoda, and calcareous algae.*

Research Needed in Engineering Geology. EDWIN B. ECKEL. Pp. 12. Colorado Sci. Soc., 1951. *A plea for geologists to use engineering methods to determine the physical properties of rocks as a step toward making their data more valuable to the engineer.*

Illinois Geological Survey—Urbana, 1951.

Rept. Inv. 152. The Mississippian-Pennsylvanian Unconformity in Southern Illinois. RAYMOND SIEVER. Pp. 40; figs. 13. *An unprecedentedly detailed description of a surface of unconformity.*

Rept. Inv. 154. High Temperature Thermal Effects of Clay and Related Materials. W. F. BRADLEY AND R. E. GRIM. Pp. 20; figs. 10; tbls. 3. *A comparison of thermal, optical, and X-ray diffraction studies.*

Circ. 168. Reactions Accompanying the Firing of Brick. R. E. GRIM AND W. D. JOHNS, JR. Pp. 6; figs. 4; tbls. 2. *Application of thermal analysis to the study.*

Circ. 169. Future Oil Possibilities of the Eastern Interior Basin. DAVID H. SWANN ET AL. Pp. 13; figs. 8. *An evaluation arranged by age of the rocks.*

Circ. 170. Short Papers on Geologic Subjects. Pp. 26; figs. 18; tbl. 1. *The Mt. Simon Sandstone in Northern Illinois, by J. S. Templeton; Petrology of Basal High-Purity Bed of the Burlington Limestone, by Donald L. Graf; Preglacial Gravels in Henry County, Illinois, by Leland Horberg; The Neda Formation in Northeastern Illinois, by L. E. Workman.*

Circ. 171. Determination of Fluorine in Organic Compounds. HOWARD S. CLARK. Pp. 3; fig. 1. *Microcumbustion method.*

Press Bull. Ser. No. 63. Developments in Illinois and Indiana in 1950. ALFRED H. BELL AND R. C. COOPER. Pp. 13; fig. 1; tbls. 9. *Brief description of exploration for petroleum and table of new oil wells.*

Kansas University and Geological Survey—Lawrence, 1951.

Bull. 90, Pt. 5. Some High-Calcium Limestones in Kansas. RUSSELL T. RUNNELS. Pp. 24; figs. 3; pls. 2; tbls. 10. *14 chemical analyses.*

Bull. 91. The Manufacture of Lightweight Concrete Aggregate from Kansas Clays and Shales. NORMAN PLUMMER AND WILLIAM B. HLADIK. Pp. 100; figs. 4; pls. 7; tbls. 10. *Tests on 227 samples.*

The Mineral Industry of Missouri in 1949. O. M. BISHOP. Pp. 24; tbls. 2. Missouri Geol. Survey Inf. Circ. 7, Rolla, 1951. *Review by commodity.*

North Dakota Geological Survey—Grand Forks, 1950–1951.

Bull. 25. The Geology of the South Unit Theodore Roosevelt National Memorial Park. WILSON M. LAIRD. Pp. 18; figs. 9; pl. 1. *Brief, semi-technical report with road log; no geologic map.*

Rept. Inv. 4. Geology of the Pembina Hills. WILSON M. LAIRD. Pp. 2; fig. 1. *Non-technical description of the formation of the Hills with emphasis on sedimentation and glaciation.*

Ohio Division of Water—Columbus, 1951.

Annual Report, 1950. C. V. YOUNGQUIST. Pp. 20; figs. 15. *Report of activities.*

Bull. 23. Chemical Character of Surface Waters of Ohio, 1946–1950. WILLIAM L. LAMAR AND MERLE E. SCHROEDER. Pp. 100; pls. 3. *Tables of data with brief explanations.*

Use of Snow Surveys in Planning Regulation of Columbia River Floods. R. A. WORK, H. G. WILM, AND MORLAN W. NELSON. Pp. 29; figs. 6; tbls. 9. Oregon Agric. Exper. Station, Corvallis, July 1951.

Pennsylvania Geological Survey—Harrisburg, 1951.

Progress Rept. 135. Oil and Gas Developments in Pennsylvania in 1950. CHAS. R. FETTKE. Pp. 10; pl. 1; tbls. 7. *List of wells completed.*

Progress Rept. 137. Geology and Mineral Resources of New Florence Quadrangle, Pennsylvania. M. N. SHAFFNER. *Geologic map, with text on reverse.*

Ecological Animal Geography, 2nd Edit. W. C. ALLEE AND KARL P. SCHMIDT. Pp. 715; figs. 142. John Wiley & Sons, New York, and Chapman & Hall, London, 1951. Price, $9.50. *Based on the late Richard Hesse's "Tiergeographie auf oekologischer Grundlage," this second American edition is revised and contains some newer ideas that depart from Hesse's original concepts. The bibliography has also been revised. The 28 chapters are divided as follows: Part 1, The Ecological Foundations of Zoögeography; Part 2, The Distribution of Marine Animals; Part 3, The Distribution of Animals in Inland Waters, A Phase of Limnology; Part 4, The Distribution of Land Animals.*

Silicate Analysis—A Manual for Geologists and Chemists With Chapters on Check Calculations and Geochemical Data, 2nd Edit. Revised. A. W. GROVES. Pp. 336; figs. 11; tbls. 11. George Allen & Unwin Ltd., London, 1951. Price, 25s. *A revision that provides practical and up-to-date laboratory methods for rocks, silicate minerals, and of the silicates used in industry; the best alternative methods are pointed out, and the geochemical data has been expanded.*

Canada Department of Mines—Ottawa, 1950–1951.

Bull. 20. Precambrian Correlation and Nomenclature, and Problems of the Kisseynew Gneisses, in Manitoba. J. M. HARRISON. Pp. 53; figs. 4; pl. 1; tbls. 7. Price, 25 cts. *Study by areas.*

Mem. 259. Geology of Northeastern British Columbia. F. H. MCLEARN AND E. D. KINDLE. Pp. 236; figs. 16; pls. 8; tbls. 6; 1 geol. map. Price, $1.25. *Comprehensive compilation of all published and unpublished information.*

Publications of the Dominion Observatory, Vol. XIV, Bibliography of Seismology, No. 8, Items, 7418–7470, July to December, 1950. W. G. MILNE. Pp. 19.

Alberta Research Council—Edmonton, 1951.

Rept. 59. Geology of Carbondale River Area, Alberta. W. H. A. CLOW AND M. B. B. CROCKFORD. Pp. 70; figs. 16; pl. 1; map 1. Price, 50 cts. *Stratigraphy, structure, and economic geology.*

Rept. 61. Clay Deposits of Elkwater Lake Area, Alberta. M. B. B. CROCKFORD. Pp. 102; tbls. 52; map 1. Price, 50 cts. *Brief description of stratigraphy and structure, and detailed description of deposits.*

Conference on the Origin and Constitution of Coal. Pp. 159; figs. 30; pls. 7; tbls. 6. Nova Scotia Dept. Mines, Crystal Cliffs, 1950. *Text of eleven talks.*

Ontario Department of Mines—Toronto, 1951.

Map 1951–4. Township of Harker, District of Cochrane, Ontario. *Compiled geologic map; in color; scale, 1/12,000.*

Prel. Rept. 1951–6. Ground Investigation of Aeromagnetic Anomalies on the Campbellford and Bannockburn Sheets. W. D. HARDING. Pp. 8; figs. 2; tbl. 1. *Tabulation of aeromagnetic anomalies.*

Prel. Rept. 1951–7. Geology of the Blackwater-Beardmore Area. P. A. PEACH. Pp. 5; 1 geol. map. *Very brief description of stratigraphy and structure. Some gold prospects.*

57th Annual Report, Being Vol. LIX, Part II, 1950. Mines of Ontario in 1949. I. WILLIAMS. Pp. 109. *Comprehensive list of mines, including officers, capitalization, location, operations in 1950, and production.*

The Mineral Deposits of Gondwanaland. SIR LEWIS L. FERMOR. Pp. 45; figs. 4; tbls. 31. Inst. Min. Metallurgy Trans., London, 1951. *Statistical study of the productivity. A presidential address.*

A Glossary of Petroleum Terms. Pp. 16. Inst. Petroleum, London, 1951. *117 definitions in non-technical terms.*

The Northampton Sand Ironstone—Stratigraphy, Structure and Reserves. S. E. HOLLINGWORTH, J. H. TAYLOR ET AL. Pp. 211; figs. 18; pls. 6; tbls. 23. Great Britain Geol. Survey, London, 1951. *Stratigraphy, structure, mineralogy, and petrology of the ironstones of the Inferior Oolite age with detailed descriptions of the fields and 45 new analyses.*

Second Annual Report of the Joint Coal Board, for 1948–49. Pp. 70; tbls. 31. **Third Annual Report of the Joint Coal Board, for 1949–50.** Pp. 86; tbls. 33. Sydney, Australia, 1950–1951. *Brief reviews of production, utilization, welfare,*

education, etc., plus statistical summaries of the industry; production, prices, consumption, stock piles, stopages, and similar.

The Geology and Mineral Resources of the Fraser's Hill Area Selangor, Perak and Pahang, Federation of Malaya, With an Account of the Mineral Resources. F. W. Roe. Pp. 138; figs. 10; tbls. 15; map 1. Malaya Geol. Survey Mem. 5, Kuala Lumpur, 1951. Price, $6.00 (Straits). *Stratigraphy and brief structure, with descriptions of the individual tin deposits and a review of the other economic minerals.*

Provisional Mineral Map of Southern Rhodesia. Scale, 1/2,000,000. Southern Rhodesia Geol. Survey, Salisbury, 1951. *In color.*

Annual Report for the Year 1950. Pp. 9; tbl. 1. Northern Rhodesia Water Devel. and Irrigation Dept., Lusaka, 1951. Price, 1s. *Review of the year's activities.*

Annual Report of the Geological Survey of Sierra Leone for 1949. Pp. 8. Freetown, 1951. Price, 1s. *Review of the year's activities.*

On Contact Phenomena of the Satakunta Diabase. Aarno Kahma. Pp. 84; figs. 22; pls. 5; tbls. 10. Comm. Géol. Finlande Bull. 152, Helsinki, 1951. *Describes the occurrence and petrography of dikes at and near the contact of olivine diabase with silicic country rock and concludes they are palingenic.*

The Anorthosite and Kenningite of the Nordingrå-Rödö Region—A Contribuo the Problem of the Anorthosites. H. von Eckermann. Pp. 42; figs. 13; pls. 9. Geol. Fören. Förh., Stockholm, 1938. *Mineralogical and chemical study; origin by magmatic differentiation and rise of the plagioclase crystals to the roof of the chamber.*

Pakistan Geological Survey—Karachi, 1950.

Rec. Vol. 2, Pt. 1. The Search for Oil in Pakistan. Eric J. Bradshaw and H. Crookshank. Pp. 14; fig. 1. Price, Annas –/4/–. *A brief explanation in non-technical terms of the methods used in the search for oil, followed by notes on the oil prospects of various regions.*

Rec. Vol. 1, Pt. 2. Directory of the Economic Minerals of Pakistan. A. M. Heron. Pp. 70. Price, Annas –/14/–. *A survey by commodity and province of the mineral potential of Pakistan. Mainly descriptive.*

Annales Géologiques du Service des Mines de Madagascar, Fasc. XIII. Pp. 107; figs. 11; pls. 20. Paris, 1948. *The Eocene and Oligocene Foraminifera of Western Madagascar, by Louis Doncieux; Neo-Cretaceous Ammonites of the Menabe, by Maurice Collignon.*

Geochemische Untersuchungen an den Alaun- und Kieselschiefern Thuringens. Friedrich Leutwein. Pp. 45; figs. 12; tbls. 37. Arch. Lagerst.-Forschg., H. 82, Berlin, 1951. *Spectrographic studies of alum slates for minor elements and a discussion of their significance.*

Abhandlungen der Geologischen Landesanstalt Berlin—1950.

Heft 216. Die Beziehungen der Pericyclus-Fauna des Gr. Schachttales Zum Acker-Bruchbergsystem (Harz). Gerhard Mempel. **Die Acker-Bruchbergschichten des Harzes.** Werner Schwan. Pp. 47; figs. 55; pls. 8. *Results of stratigraphic and structural studies of the Acker-Bruchberg strata in the Harz Mountains.*

Heft 219. Über Lösung und Hydratation des Anhydrits. JOACHIM OTTEMANN. Pp. 16; figs. 5; pls. 8. *Results of solubility and microscopic studies of anhydrite for use as a substitute for gypsum in plasters and other binders.*

Pflanzenabdrücke aus dem Alttertiär von Mosel bei Zeickau in Sachsen. EMIL FISCHER. Pp. 28; figs. 8; pls. 10. Abh. Geol. Dienst. Berlin, H. 221, 1950. *A study of Paleogene fossil leaves near Mosel, Saxony.*

Annales de la Société Géologique de Pologne, Vol. XX, Fasc. 1–2, 1950. Pp. 212; pls. 9; figs. 7. Krakow, 1951. *Ore veins on Ornak in the Western Tatra Mountains; Contribution to the Petrography of the Hnilec Mountains; Chemical Composition of Biotites in Different Rocks of the Tatra Mts.; Exotic Diabase in the Karpatic Cretaceous; Preparation of Thin Sections for Brittle Rocks.*

Przegląd Górniczy Miesięcznik, Vol. 7, Nos. 1–6. Katowice, 1951. *Includes articles on the influence of coal ash on the suitability of coal, technical and economical value of gaseous fuels, technological problems of oil shale treatment, laboratory determination of the spontaneous combustion of peat, and numerous articles on mining techniques and practices, especially for coal.*

SOCIETY OF ECONOMIC GEOLOGISTS

MEETING OF THE SOCIETY AT ALGIERS, SEPTEMBER 1952.

Arrangements have been made to hold a meeting of the Society of Economic Geologists during the 19th Session of the International Geologic Congress, to be held at Algiers, between September 8th and 15th, 1952. This meeting will be followed by a dinner for members of the Society and invited guests.

The purpose of the meeting, in addition to furthering mutual acquaintance and understanding among our widely distributed membership, is to consider ways in which the international character of the Society may be further emphasized. Suggestions will be received and discussed regarding possible methods to make the Society more useful to members of our profession residing outside the North American continent (now forming about one-sixth of our total membership). Suggestions have been made that it might be appropriate for the Society to support the formation of regional sections, and also to encourage the publication of outstanding papers in languages other than English.

M. Fernand Blondel has kindly agreed to take charge of all arrangements for the meeting and would be glad to receive suggestions along this line which may merit discussion at the meeting.

It will also be of advantage to members of the Society to notify M. Blondel at an early date of the Congress excursions in which they desire to participate, in order that the necessary reservations may be made. As far as possible, members will be assigned to excursions of their choice, covering fields in which they are particularly interested.

Please communicate directly with F. Blondel, 12 Rue de Bourgogne, Paris (7°), France.

OLAF N. ROVE,
SECRETARY.

SOCIETY OF ECONOMIC GEOLOGISTS

JOINT TECHNICAL SESSIONS OF THE SOCIETY OF ECONOMIC GEOLOGISTS AND THE GEOLOGICAL SOCIETY OF AMERICA, TO BE HELD AT DETROIT, MICHIGAN, NOVEMBER 8–10, 1951.

Friday Afternoon, Grand Ballroom.

Economic Geology.

Carl Dutton and William James, *Co-chairmen.*

(After each paper 5 minutes is allowed for discussion.)

1. 2:00 Hugh McKinstry: *Structure and copper mineralization at the Elizabeth Mine, Vermont.*
2. 2:20 F. G. Snyder: *Stratigraphic studies of graywackes at Ducktown, Tennessee.*
3. 2:40 Kenneth K. Landes: *The origin of thick-bedded salt deposits.*
4. 3:00 Paul Hammond: *The Allard Lake ilmenite deposits.*
5. 3:25 J. A. Retty and A. E. Moss: *Iron ore deposits of New Quebec and Labrador.*
6. 3:50 E. F. Fitzhugh, Jr.: *Iron ore at Bomi Hill, Liberia.*
7. 4:10 Paul K. Sims: *Structure of the magnetite deposits in the Dover district, New Jersey.*
8. 4:30 Richard M. Foose: *Ground-water behavior in the Hershey Valley, Pennsylvania.*
9. 4:45 Harry E. Legrand: *Solution depressions in diorite in North Carolina.*

Saturday Morning, Wayne Room.

General Geology.

J. K. Gustafson and Arthur Lang, *Co-chairmen.*

(After each paper 5 minutes is allowed for discussion.)

1. 9:00 Donald L. Everhart and Robert J. Wright*: *Some geologic characteristics of uranium-bearing vein deposits.*
2. 9:20 John W. Gruner,* Charles C. Towle, and Lynn Gardiner: *Uranium mineralization in Todilto limestone near Grants, McKinley County, New Mexico.*
3. 9:35 B. S. W. Buffam: *Uranium deposits—Beaverlodge area, Saskatchewan, Canada.*
4. 9:55 J. C. Olson * and W. N. Sharp: *Geologic setting of the Mountain Pass bastnaesite deposits, San Bernardino County, California.*
5. 10:15 Charles E. Weaver * and Thomas F. Bates: *Mineralogy, petrography, and petrology of the K-bentonites.*

* Indicates speaker.

6. 10:35 T. S. Lovering and H. D. Goode: *Relation of factors affecting ground and rock temperature at shallow depths.*

7. 10:55 J. E. Lamar * and Raymond S. Shrode: *Water-soluble salts in limestones and dolomites.*

8. 11:15 Helen L. Foster * and Arnold C. Mason: *1950 and 1951 eruptions of Mihara Yama, O Shima volcano, Japan.*

SATURDAY MORNING, IVORY ROOM.

ECONOMIC GEOLOGY (SEG COAL COMMITTEE.)

W. V. Searight and Paul Averitt, *Co-chairmen.*

(After each paper 5 minutes is allowed for discussion.)

1. 9:00 B. C. Parks and H. J. O'Donnell: *Petrographic analysis of column samples by combined thin-section and broken-coal method with results on a sample of No. 6 coal from St. Clair County, Illinois.*

2. 9:25 P. C. Hacquebard: *Opaque matter in coal.*

3. 9:50 J. T. McCartney: *Study of the Seyler theory of coal reflectance.*

4. 10:15 Raymond Siever: *X-ray diffraction studies of some physical components of coal.*

5. 10:30 W. J. Smothers and Yao Chiang: *Differential thermal curves of some Arkansas lignites.*

6. 10:45 William W. Hambleton: *Practical significance of the petrographic constituents of two Kansas coal beds.*

7. 11:00 Robert M. Kosanke: *Chemical analyses of constituents of clarain.*

8. 11:15 W. L. Whitehead and Lewis H. King: *Vacuum differential thermal analysis of coal.*

SATURDAY AFTERNOON, IVORY ROOM.

ECONOMIC GEOLOGY (SEG COAL COMMITTEE.)

Harold Wanless and G. H. Cady, *Co-chairman.*

(After each paper 5 minutes is allowed for discussion.)

1. 2:00 Paul Averitt: *Status of summary coal resource surveys, November 1, 1951.*

2. 2:25 Jack A. Simon: *Report on the Third Conference on Carboniferous Stratigraphy and Geology at Heerlen, Netherlands, June 25–30.*

3. 2:40 E. C. Dapples: *Sedimentary facies changes in coal strata.*

4. 3:00 E. P. Du Bois: *Interrelation of structure and Pennsylvania sedimentation in Central Illinois.*

5. 3:15 Charles E. Wier: *Some recent correlations of Indiana coals.*

6. 3:30 G. K. Guennel: *Spore analyses applied to a coal correlation problem in southern Indiana.*

7. 3:45 George M. Wilson: *Underclay limestones.*

8. 4:00 Discussion of coal geology literature for 1951 by members of SEG Coal Committee, and Business Meeting.

* Indicates speaker.

Abstracts of papers to be presented at the joint meeting of the Society of Economic Geologists and the Geological Society of America at Detroit, Michigan, November 8–10, 1951.

STRUCTURE AND COPPER MINERALIZATION AT THE ELIZABETH MINE, VERMONT.

HUGH MCKINSTRY.

Discovered in 1793 and worked at several periods since then, the Elizabeth mine has produced about 55 million pounds of copper of which some 45 million pounds represents production since reopening in 1943. The copper occurs as chalcopyrite associated with massive pyrrhotite. The sulphides form plunging pod-like lenses, one of which has been mined continuously throughout a plunge-length of over 5,000 feet to a present depth of 975 feet lower than the outcrop. The lenses are replacement bodies in tightly folded sediments which are now metamorphosed to biotite schists. The ore bodies lie in the crease of an overturned syncline. In a broad way they are localized by plunging folds, and in greater detail by strongly deformed zones adjoining strike-faults.

STRATIGRAPHIC STUDIES OF GRAYWACKES AT DUCKTOWN, TENNESSEE.

F. G. SNYDER.

The pyrrhotite-pyrite-chalcopyrite ore bodies of the Ducktown Basin are localized in favorable zones in a thick graywacke-schist sequence. The formations have been subjected to at least two periods of folding and are cut by three fault systems.

Graded bedding and poor sorting are characteristic of the graywackes. Medium rank metamorphism has resulted in each normal graded bed being transformed into a graywacke-schist pair. The coarse clastic material forming the lower part of the bed is relatively unchanged; the finer material of the upper part of the bed has been metamorphosed to a mica schist. In addition to the cyclical repetition of graywacke and schist beds, a larger scale alternation of groups of beds that are dominantly graywacke with groups that contain more schist than graywacke is evident. The sulfide deposits lie in zones in which schist is abundant.

Lateral gradation from one rock-type to another is common throughout the Basin and is especially prominent in the mineralized areas. This facies change appears to have been an important factor in localizing the ore deposits, probably because of differences in structural behavior of rocks of different competency.

Normal stratigraphic methods have been supplemented by detailed study of heavy accessory minerals. Ilmenite is an abundant constituent of some beds. It is useful in tracing beds in the field and in deciphering complex structures. Minute grains of detrital zircon can be easily distinguished in drill core with the aid of a shortwave ultra-violet light. Zircon logging of drill core is useful in correlating formations cut in diamond drill holes.

THE ORIGIN OF THICK-BEDDED SALT DEPOSITS.

KENNETH K. LANDES.

The following stages are suggested in the natural history of a major bedded salt deposit:

1. Peneplanation of the continental platform so that it is a nearly flat land of very little elevation above the sea.
2. Submergence of wide areas beneath the sea. Shallow ocean waters spread over a considerable part of the continent.

3. Beginning or renewed downwarping of a basin marginal to this epicontinental sea.

4. Sedimentation of both basin and epicontinental sea. Mainly clastic and organic (reef) deposits.

5. Lowering of sea to approximately sill level. Period of evaporite deposition. Enrichment by sea water flowing across sill. Because of the shallowness of the water, and the distance from the open ocean in such areas as the Michigan Basin, the brine crossing the sill may have been abnormally strong due to a relatively high evaporation rate.

No doubt there was also some dilution taking place by streams entering the subsiding basin from the surrounding lands. The terranes drained by the streams entering these ancient basins were mainly shale and carbonate rock. Therefore the streams during times of normal flow brought in calcium and magnesium carbonate in solution. During flood stages fine sediment obtained from the outcropping shale and carbonate rock was carried in suspension into the silled basin. This situation has not been simulated in the chemical laboratory.

THE ALLARD LAKE ILMENITE DEPOSITS.

PAUL HAMMOND.

The Allard Lake ilmenite deposits lie in the northeastern part of one of the large anorthosite masses of Precambrian age which are exposed at intervals along the north shore of the St. Laurence River, in Quebec. The ore bodies, themselves, consist of a series of narrow dikes, irregular lenses, or sill-like bodies which appear to bear a genetic relationship to the anorthosite rocks in which they occur. The ore itself is a black, coarse-grained aggregate of ilmenite, which holds numerous oriented microscopic lamellae of hematite. Grade of the material classed as ore averages 32 percent Fe.

This paper deals with the regional geology of the Allard Lake area, and with the geology of the ore deposits themselves. The Lac Tio deposit, which is the largest body of titanium ore of its type now known in the world, is discussed in detail. The pattern of geological and geophysical exploration is outlined, from original discovery to ultimate exploitation of the ore. Brief mention is made of the methods of development of the deposits, and of the present and potential uses of titanium pigments and titanium metal.

IRON ORE DEPOSITS OF NEW QUEBEC AND LABRADOR.

J. A. BETTY AND A. E. MOSS.

The proved iron ore deposits lie within a northwest-trending zone, 90 miles long and 12 miles wide, close to or astride the Quebec-Labrador boundary in the vicinity of latitude 54° 48′ N. and longitude 66° 50′ W.

The ores occur in iron formation near the top of some 2,500 feet of Proterozoic sedimentary rocks resting on Archeozoic gneiss. These sedimentary rocks are in the "Labrador trough" which extends at least 500 miles northward from the central part of the Labrador peninsula. They consist in ascending order of slates, dolomite, chert breccia, quartzite, slate, iron formation, and more slate, intercalated locally with volcanic flows. The assemblage is cut by diabase dikes, diorite and gabbro. On the southwest tip, it is intruded and metamorphosed by a granite batholith. The iron bearing portion is thirty miles across. In the northeast portion of the area there is an additional thirty miles of volcanics with minor sediments cut by serpentinite, diorite, and gabbro. These rocks are of uncertain age, but younger than the gneiss.

All of the rocks have been folded and thrust-faulted by a stress from the northeast, the resultant trend being generally northwest.

The ores consist of "limonite," hematite (some martite) and minor magnetite. Twelve percent of the reserves is manganiferous. Some ore bodies occur along faults, others in the noses of folds, still others along straight limbs of folds. All probably were localized in permeable fracture zones resulting from regional deformation.

The ores were formed by meteoric waters acting on iron formation containing about 30 percent iron, predominantly as oxides, less importantly as carbonate and silicates. These waters leached out silica and precipitated large quantities of iron oxide in the iron formation.

To the end of 1950, the reserve indicated by drilling was 417,707,000 long tons of high-grade, direct shipping, open pit ore. There are in addition very large, but unmeasured tonnages of lower grade wash ore and ore that may ultimately be concentrated by gravity methods. Virtually untested by drilling or trenching are thousands of square miles of iron formation containing unknown tonnages of additional ore for the more remote future.

IRON ORE AT BOMI HILL, LIBERIA.

E. F. FITZHUGH, JR.

The ore and siliceous iron formation at Bomi Hill, Liberia, are similar in character and occurrence to the better-known deposits of Venezuela and Brazil. Iron formation forms a hanging wall and granite gneiss a footwall of the massive, high-grade ore. Ore outcrops and float show induration and recrystallization to a fine-grained, "steely hematite." Similar transformations by tropical meteoric waters in Venezuela are noted. Canga capping is confined to the hanging-wall side of the Bomi Hill ore. This, together with comparable occurrences in Venezuela, suggest that the iron in porous limonitic canga is derived from iron-rich, siliceous rocks rather than from high-grade iron ore.

STRUCTURE OF THE MAGNETITE DEPOSITS IN THE DOVER DISTRICT, NEW JERSEY.[1]

PAUL K. SIMS.

The magnetite deposits in the Dover district, within the New Jersey Highlands, are Precambrian in age and replace oligoclase-quartz-biotite gneiss, soda granite, hornblende skarn, and pyroxene skarn. The country rock is deformed into isoclinal folds that trend and plunge northeast.

The deposits in gneiss, soda granite, and hornblende skarn are unusual lath-shaped bodies whose longitudinal planes are essentially parallel to the foliation and whose longitudinal axes are parallel to the lineation in the country rock. Some ore bodies have been mined for as much as 11,000 feet along their pitch length, and the end of an ore body has never been reached. The deposits in pyroxene skarn are probably lenticular or podlike, and they resemble other skarn deposits in the New Jersey Highlands and elsewhere.

The magnetite deposits are linear or curved; they occur on the limbs or in the axial regions of folds. The deposits in gneiss and granite occupy microbreccia zones, which tend to parallel the axial planes of the folds and which generally are parallel to the gneissic structure of the country rock, except locally where they cut sharply across it. The microbreccia zones, which were formed by pre-ore cataclastic deformation, were favorable structures for the localization of the ore bodies.

[1] Published by permission of the Director, U. S. Geological Survey.

GROUND WATER BEHAVIOR IN THE HERSHEY VALLEY, PENNSYLVANIA.

RICHARD M. FOOSE.

The Hershey Valley, part of the Great Valley, is situated nine miles east of Harrisburg, Pennsylvania. Beekmantown limestone (Ordovician), striking N70E and steeply overturned to the southeast underlies the valley.

The Annville Stone Company mines the high-calcium Annville limestone (top of the Beekmantown) one and a half miles northeast of the Hershey Chocolate Corporation plant. For many years 3,500 gallons per minute was the normal pumping discharge. Neither industry adversely affected the other nor any of the valley residents.

Plans of the Stone Co. to mine at lower levels prompted geologic studies by the Chocolate Corporation. One hundred wells and springs in the valley were systematically observed, 15 of the most critical being measured every two weeks. For each there was determined the water elevation; water temperature; pH value; ppm of dissolved solids; ppm of the Ca, Mg, PO_4, SiO_2, Al_2O_3, SO_4, and Fe ions; and yield in gallons per minute of the springs. Details of ground water movement were studied by using fluorescein. Piezometric maps of the valley were periodically made.

When the mine began pumping 6,500 gallons per minute from lower levels in May 1949 it drastically lowered the ground water level over an area of 10 square miles, drying up all valley springs and many wells. About 100 sink holes of all sizes developed in the area, endangering life and property. The piezometric map of November 1949 showed a huge cone of depression with the apex at the mine.

Ground water levels were successfully restored over a large area when the Chocolate Corporation recharged water to the ground, beginning December 1949.

SOLUTION DEPRESSIONS IN DIORITE IN NORTH CAROLINA.[1]

HARRY E. LEGRAND.

During 1950 more than 40 enclosed depressions, resembling sinks of limestone terranes, were observed by the writer in the igneous rocks of the Piedmont plateau of North Carolina. These depressions, averaging about 200 feet in diameter and about 3 feet in depth below the lowest possible overflow point, are restricted to upland areas of dioritic rocks.

That the agents of subaerial erosion are apparently incapable of forming these enclosed depressions indicates that ground water is the principal agent in forming them. The evidence indicates that soluble rocks underly the depressions, that an appreciable amount of dissolved mineral matter is extracted from the dioritic rocks by ground water, and that surface subsidence is a consequence. More than three times as much mineral matter is extracted by circulating ground water from diorite as from granite, the most common rock of the Piedmont.

Solution subsidence is not confined to the enclosed depressions but is even more active in valley heads where the ground water circulation and the consequent solution are greater. Studies in the Piedmont of the occurrence and movement of ground water and an appraisal of data on the quantity and chemical quality of natural water reveal that ground water is a more significant agent in the erosion of igneous rocks than is generally believed.

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SOME GEOLOGIC CHARACTERISTICS OF URANIUM-BEARING VEIN DEPOSITS.

DONALD L. EVERHART AND ROBERT J. WRIGHT.

The geologic characteristics of primary pitchblende-bearing vein deposits in twelve significant districts throughout the world have been compiled and appraised. Special consideration has been given to: 1) the nature and age of the host rocks, 2) mineral associations in the deposits, 3) the paragenesis of the vein minerals, 4) structural relationship of the veins, and 5) hydrothermal wall rock alteration, where it has been observed.

Three major structural belts in the earth's crust contain uranium-bearing vein deposits. These are found in western Europe and Africa, the western margin of the Canadian Shield, and the Cordillera of North and South America. Deposits in each of these belts appear to have in common certain geologic characteristics and ages of mineralization.

The present survey indicates that: 1) the most favorable host rocks are felsic igneous intrusive rocks and siliceous metasediments, 2) the common associated metallic minerals are copper, cobalt, silver, and lead sulfides and sulfarsenides and iron oxides, 3) the common gangue minerals are various forms of silica, iron-bearing carbonates, fluorite, and barite, and 4) the paragenetic position of pitchblende in the veins is variable, probably due to the fact that it is deposited from a colloidal solution and the deposition, therefore, was not closely controlled by temperature.

Pitchblende deposits are largely emplaced within tensional structures that are commonly minor fractures associated with large-scale structures.

URANIUM MINERALIZATION IN TODILTO LIMESTONE NEAR GRANTS, MCKINLEY COUNTY, NEW MEXICO.

JOHN W. GRUNER, CHARLES C. TOWLE, AND LYNN GARDINER.

Uranium ores have been found in Todilto limestone near Grants, New Mexico, about 75 miles west of Albuquerque. The rocks are a part of the southern rim of the San Juan Basin and dip gently northward. The Todilto is practically conformably underlain by Entrada sandstone. Summerville formation overlies it. The limestone in the area under discussion varies from 3 to 20 feet in thickness. Usually, the upper part shows considerable recrystallization. It is in this portion that most of the mineralization is found. Here, the minerals carnotite, tyuyamunite, uranophane, and some amorphous, ill-defined uranium-vanadium compounds partly replace the calcite. Fluorite has been found in two places replacing calcite. Pitchblende in minute blebs has been identified. The lower, thinly bedded limestone contains the uranium only along joints and fractures. Very minor amounts of uranium mineralization have been discovered in the basal few feet of the overlying Summerville. It may be stated tentatively that the uranium content is probably of syngenetic origin. Diagenesis caused recrystallization of the upper Todilto and some concentration of the ore. Circulating ground water caused much later solution and reprecipitation in the ores.

URANIUM DEPOSITS—BEAVERLODGE AREA, SASKATCHEWAN, CANADA.

B. S. W. BUFFAM.

The Beaverlodge uranium deposits are located on the north shore of Athabasca Lake, Saskatchewan, Canada. The deposits occur in Proterozoic rocks. The Tazin series consisting of highly altered quartzite, shale, arkose, etc., is overlain unconformably by the Athabasca series consisting of conglomerate arkose and inter-

calated basalt and andesite flows. Two strong NE–SW faults, the St. Louis and the Crackingstone, are recognized. It is inferred that the many tensional fractures and shattered zones in which the uranium mineralization is found are principally related in many instances to stresses developed by movements along these faults.

In an area of approximately 120 square miles in the Beaverlodge District, many hundreds of isolated occurrences of pitchblende have been noted. At present, one deposit—the Ace—is being prepared for production. Five deposits—Eagle, Martin, Nicholson, Rix and Nesbitt-Labine—are being tested underground. Surface exploration and diamond drilling suggest that an additional five deposits—Cinch, Amax, Aurora, Pitchore and Fishook—probably warrant exploration underground.

The pitchblende in the majority of the deposits occurs as plates and thin veinlets in irregular discontinuous tension fractures or as scattered small masses and local disseminations in wide breccia zones. The host rocks are usually impregnated with red, dusty hematite. Pitchblende is generally associated with pyrite and chalcopyrite and minor amounts of minerals containing cobalt, nickel, lead and zinc. The non-opaque gangue minerals with the pitchblende comprise calcite, chlorite and quartz.

GEOLOGIC SETTING OF THE MOUNTAIN PASS BASTNAESITE DEPOSITS, SAN BERNARDINO COUNTY, CALIFORNIA.[1]

J. C. OLSON AND W. N. SHARP.

Bastnaesite-bearing carbonate rocks at Mountain Pass, California, are related to potash-rich intrusive rocks, possibly of Mesozoic or Tertiary age, that cut Precambrian injection gneiss and granitic gneisses. The larger intrusive masses, 300 or more feet wide, comprise one granite, two syenite, and four composite shonkinite-syenite bodies. One of the shonkinite-syenite bodies is more than a mile long. Several hundred relatively thin dikes of these potash-rich rocks range in composition and generally decreasing age from biotite shonkinite through syenite to granite. These rocks are cut by east-trending andesitic dikes and by faults, two of which form the west and north boundaries of known rare earth mineralization.

Carbonate rocks and bastnaesite are most abundant in and near the southwest side of the largest shonkinite-syenite body. Although most bodies of carbonate rock are less than 6 feet wide, one large mass found in 1950 has a maximum width of 600 feet and is 2,400 feet long. Calcite is the chief carbonate mineral in this body; the remainder of the rock is composed of barite, bastnaesite, and variable small quantities of quartz, crocidolite, biotite, chlorite, apatite, iron oxides, fluorite, galena, and monazite. Additional minerals will probably be found by further study. The rare earth oxide content in most of the carbonate rock is less than 13 percent, but in some local concentrations of bastnaesite the content is as high as 40 percent.

Rocks in the Mountain Pass area show certain petrogenetic similarities with rocks in Alnö Island, Sweden; Fen, Norway; and some localities in South Africa. Structure and composition suggest that the large carbonate body is genetically related to the differentiation of an alkaline magma.

MINERALOGY, PETROGRAPHY AND PETROLOGY OF THE K-BENTONITES.

CHARLES EDWARD WEAVER AND THOMAS F. BATES.

A detailed mineralogical and petrographic study of 22 potassium-bentonites (metabentonites) from the Ordovician of Central Pennsylvania revealed that they are composed of randomly interstratified layers of non-expanded, K based montmorillonite and expanded, Ca, Mg, and Na based montmorillonite in the approxi-

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mate ratio of 4:1. Several of the clays contain a small amount of chlorite in the form of packets. Chlorite is the cause of one of the two hydroxyl-endothermal reactions in this material and is probably responsible for one of the peaks of similar double reactions which have heretofore been assigned to the individual mineral components of mixed layer clays.

A study of 27 samples of the limestone above and below the K-bentonite showed that the rock in immediate contact contains the same types of clay. However, farther from the beds the clays consist of three, unmixed clay minerals: non-expanded montmorillonite (illite), expanded montmorillonite and chlorite.

It is thought that the criteria for the division of clays of the 2:1 structure type into two groups are not fundamental and the suggestion is made that these clays be classified on the basis of the chemical composition of the impure pyrophyllite-talc structural unit rather than upon the characteristics which are a direct reflection of the interlayer cations.

The K-bentonites contained angular volcanic glass and albite, idiomorphic apatite, zircon, and biotite. The limestones contain idiomorphic quartz, albite, apatite, zircon, and xenomorphic biotite.

RELATION OF FACTORS AFFECTING GROUND AND ROCK TEMPERATURE AT SHALLOW DEPTHS.[1]

T. S. LOVERING AND H. D. GOODE.

The depth-temperature curve for shallow depths results from the geothermal gradient and changes in temperature at the surface. The depth of penetration of cyclical diurnal and annual temperature changes is controlled by the thermal diffusivity and the period and range of temperature change at the surface.

The range of daily temperature changes attenuates rapidly with depth; in gravel the diurnal change at 10 centimeters is 42 percent of the diurnal change at the surface. It is 8 percent at 30 centimeters and 0.02 per cent at 100 centimeters; in limestone and quartz latite, however, rocks of twice the diffusivity of gravel, the corresponding changes are 55 percent at 10 centimeters, 16 percent at 30 centimeters, and 0.2 percent at 100 centimeters.

The *annual* range in temperature on the other hand is perceptible to substantial depths. In quartz latite and limestone the range at 5 meters is 21 percent of the annual range at the surface, it is 4 percent at 10 meters, and 0.2 percent at 20 meters. This is equivalent to a range of 11.55° F, 2.20° F, and 0.11° F, in the East Tintic district, Utah, in 1950. Temperature measurements made here throughout the year at the surface and in drill holes showed that in the observed depth-temperature curves, the geothermal gradient was a factor additive to the calculated annual temperature variations. If, then, the surface temperature variation, the diffusivity of the rocks, the actual temperatures at various depths below the surface, and the time at which the temperatures were measured are all known, it is possible to calculate the geothermal gradient from relatively shallow holes. The difficulty of getting adequate data for precise calculations is substantial, however, and even under ideal conditions it is difficult to establish the geothermal gradient in holes less than 10 meters deep, if the rocks have thermal constants approximating those of limestone. Mean air temperatures and mean ground temperatures were found to differ substantially from average ground temperature, and the reasons for this difference are discussed. In holes 15 to 20 meters deep it is possible to get fairly reliable indications of the geothermal gradient if readings are made through a period of several months. Anomalous geothermal gradients related to comparatively strong local heat sources such as oxidizing pyrite can be quickly ascertained in holes 30 meters deep; a local gradient not appreciably higher than the normal gradient might be difficult to determine at this depth unless a substantial amount of time was spent in obtaining background information for the region under investigation.

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WATER-SOLUBLE SALTS IN LIMESTONES AND DOLOMITES.[2]

J. E. LAMAR AND RAYMOND S. SHRODE.

Leaches have been prepared from typical samples of most of the principal limestone and dolomite formations in Illinois by grinding the samples in distilled water and removing the resulting pulverized stone by filtration. Quantities of solids recovered from the leaches range between .04 and .30 percent by weight of the original rock sample. Samples 300 feet apart from the same bed showed reasonable similarity as to the amount and character of water-soluble salts. Chemical analyses and X-ray diffraction data reveal that the solids resulting from the evaporation of the leaches are composed principally of one or more of the following compounds: sodium chloride, calcium sulfate, calcium carbonate, and magnesium sulfate. Less commonly present are potassium chloride and magnesium chloride. Leaches from dolomites generally yield a greater percentage of solids than those from limestones. Probably most or all of the water-soluble salts occur as solids in the parent limestones or dolomites rather than as liquid inclusions.

PETROGRAPHIC ANALYSIS OF COLUMN SAMPLES BY COMBINED THIN-SECTION AND BROKEN-COAL METHOD WITH RESULTS ON A SAMPLE OF NO. 6 COAL FROM ST. CLAIR COUNTY, ILLINOIS.

B. C. PARKS AND H. J. O'DONNELL.

Column samples completely representative of the full thickness of coal beds under investigation are collected for thin sectioning and microscopic analysis. The analysis gives quantitative information relative to proportion of coal components present which permits type classification in accordance with Bureau of Mines, method.

Supplementary information concerning physical characteristics is obtained by petrographic study of the coal reduced to small particle sizes. The technique involves controlled crushing, size classification with sieves, gravity classification with heavy liquids, and visual classification and quantitative estimation of coal and non-coal particles with aid of stereoscopic microscope. Ash and sulfur determinations are made in connection with the petrographic analysis.

The two petrographic methods of studying coal are discussed in the paper with results of a combined analysis of a column sample of Illinois No. 6 coal collected for hydrogenation tests.

The thin section analysis revealed a bright type coal predominantly anthraxylon, 65 percent, with minus 3 percent opaque attritus. Petrographic composition of the coal exclusive of mineral matter was rather uniform. Pyrite in small crystals was found disseminated through much of the anthraxylon.

Results of broken coal analysis and ash and sulfur determinations demonstrated that no big reduction of ash and sulfur could be expected by commercial coal cleaning. The relatively large amount of ash-forming mineral matter including the pyrite found in the basal 15 inches of the coal suggests that mining the coal above the blue band would yield a product which would not be materially further improved in commercial coal cleaning.

OPAQUE MATTER IN COAL.

P. A. HACQUEBARD.

The polished surface technique is used to study the nature and occurrence of opaque matter in coal. The appearance of the opague matter under reflected light

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was determined from a polished, thin section, in which the opaque constituents were first established under transmitted light.

Two distinctly different forms of opaque matter are recognized, namely fusain lenses and opaque attritus. Based upon the presence or absence of a botanical structure, the opaque attritus is subdivided into two groups of opaque ingredients. For those devoid of structure the term micrinite is used. Micrinite occurs in three forms: finely divided granular, massive and as groundmass. Opaque attritus with structure consists of fusinite, semifusinite and sclerotinite (fungal tissue).

Evidence for the origin of the opaque attritus during the early stages of coal formation is given. A distinction is made between the opaque matter of "primary" origin, and the opacity of the high ranking coals, which is due to increased coalification. It is shown that in anthracite the opaque matter of "primary" origin can be recognized under reflected light with the aid of etched, polished sections. No increase in the amount of "primary" opaque matter with increase in rank has been observed.

The percentage of opaque matter is determined with an integrating stage, using polished specimens of ground coal, mounted in lucite. The results are compared with the proximate analyses of the coal investigated. They show that a high percentage of opaque matter corresponds with a high percentage of fixed carbon and usually a high percentage of ash.

Photomicrographs illustrate the paper.

A STUDY OF THE SEYLER THEORY OF COAL REFLECTANCE.

J. T. MCCARTNEY.

Investigations of the optical properties of the petrographic constituents of coal are reviewed and a summary is given of the Seyler theory that the components of coal derived from woody tissue, such as anthraxylon and fusain, have reflectances that can be arranged in a discontinuous series. A description is given of the apparatus used to test this theory. The application of accepted reflectance theories to results obtained with this equipment on standard minerals is described and the accuracy and duplicability of determinations on these minerals and on coal are calculated.

Graphical results are given of two procedures for testing the Seyler theory. The results are discussed and a general appraisal of the theory is presented. It is concluded that Seyler's theory is not substantiated by this study, but that his descriptions of reflectance variations in the constituents of coal may be of considerable value in petrographic analysis.

X-RAY DIFFRACTION STUDIES OF SOME PHYSICAL COMPONENTS OF COAL.[2]

RAYMOND SIEVER.

In attempts to determine some of the physical changes that accompany increase in rank in banded bituminous coals, small samples of several of the homogeneous physical components of coal, vitrains, fusains, resin rodlets, waxes, cutinite, and spore-exines, were isolated and studied by X-ray diffraction techniques. Monochromatic radiation from molybdenum, copper, and cobalt targets was used with a Laue type of camera. The patterns obtained from this method were adequate to evaluate interplanar spacings, particle size, and preferred orientation of particles.

The only diffraction lines given by the vitrains and fusains which are at all sharply defined are the 002 rings corresponding to a spacing of about 3.4 A. All the other diffraction maxima are more or less diffuse haloes of low intensity. All

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of the samples show a large amount of low-angle scattering, partly due to radiation that was not absolutely monochromatic. The diffraction lines given by the resinic components, waxes, and cutinite, are much sharper than those of vitrains and fusains and indicate that there is a greater percentage of material in these compounds that is crystalline.

Only tentative conclusions as to changes of structure with increasing rank can be drawn from this preliminary investigation. There is a suggestion from the measured values of the interplanar spacings in the higher rank coals that the carbon rings tend to approach each other more closely in a direction normal to the 002 planes, the planes in which the carbon rings lie.

DIFFERENTIAL THERMAL CURVES OF SOME ARKANSAS LIGNITES.

W. J. SMOTHERS AND YAO CHIANG.

The differential thermal method was used to obtain curves on ten samples of Arkansas lignites. A curve of high purity alpha cellulose was also run. The samples were −100 mesh and diluted with alumina. Most of the curves had a low temperature endothermic peak and two exothermic peaks at higher temperatures. In some cases a third exothermic peak was observed.

To verify the theory proposed for explanation of the various peaks, curves were obtained on oven-dried samples and also curves of the lignites under neutral atmosphere.

X-ray diffraction patterns were obtained on the lignites using a Norelco, Geiger-counter type machine.

PRACTICAL SIGNIFICANCE OF THE PETROGRAPHIC CHARACTERISTICS OF TWO KANSAS COAL BEDS.

WILLIAM W. HAMBLETON.

The Mineral and Bevier coals of the southeastern Kansas coal field are remarkably uniform in chemical composition and are noteworthy because of their finely banded character. Translucent attritus is the principal petrographic constituent. The mineral content of the coals consists mainly of calcite and pyrite but there are lesser amounts of aragonite, marcasite, sphalerite, quartz, apatite, and clay minerals.

The petrographic composition of the coals is related to several chemical and physical properties. Principal consideration is given to the friability of the coals and to their amenability to hydrogenation. It is shown that a linear relation exists between the content of anthraxylon plus fusain and the fines which result from crushing coal. On the basis of the opaque attritus content, the coals will probably hydrogenate readily. The characterization of coal in terms of friability and opacity ratios is suggested. The distribution of mineral matter in Kansas coal is of such a character that the preparation of low ash coal concentrate is probably not economically feasible.

CHEMICAL ANALYSES OF CONSTITUENTS OF CLARAIN.[2]

ROBERT M. KOSANKE.

The banded ingredients of Illinois coal beds, as viewed megascopically, are vitrain, clarain, durain, and fusain. Vitrain and fusain from Illinois coal beds have received attention from various authors.

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Studies of clarain were begun because it frequently comprises 70 to 80 percent of the coal beds, and differs both megascopically and microscopically from vitrain and fusain. Megascopically clarain varies in luster from bright to dull and microscopically is a heterogeneous unit. It usually contains translucent humic degradation matter, spores, resins, cuticle, waxes, and mineral matter. A chemical analysis is therefore an average of this heterogeneous grouping.

In an effort to understand variations in chemical analyses and combustion characteristics, it was decided to explore the role played by the individual constituents of clarain. Employing several different methods, spores, resin rodlets, and cuticle were isolated and microchemical analyses run. The carbon content of the resin rodlets exceeds 75 percent while that of the spores and cuticle is much lower, 58 to 63 percent. Differences of this sort may provide information relative to the variations noted in chemical analyses and combustion characteristics.

VACUUM DIFFERENTIAL THERMAL ANALYSIS OF COAL.

W. L. WHITEHEAD AND LEWIS H. KING.

Samples of 15–100 mgs of various coal constituents were used for differential thermal analysis in vacuum and were heated at the rate of 20° C per minute.

The thermograms are thought to present a graphic representation of some of the physical changes that take place during the carbonization process. Most constituents show an exothermic peak in the carbonization range. The temperature at the beginning of the peak is considered to be the softening point of the coal, while the temperature at which the peak reaches a maximum is thought to be the solidification point. The softening temperature is often made obscure by an effect which is inherent in the instrument.

A comparison of the temperatures at which vitrain peaks attain a maximum gives a measure of their relative rank, that is, the higher the temperature at which the maximum of the peak occurs the higher the rank. This relation is illustrated by a series of curves from lignite to semi-anthracite.

Analyses of vitrains from columnar samples of the Harbour and Emery seams in Sydney, Nova Scotia, reveal that there is no change in the temperature at which the peaks reach a maximum for bands of vitrain within each sample, but temperatures for samples from the Emery seam are from 10° C to 20° C higher than for those from the Harbour. The Emery seam is stratigraphically below the Harbour.

A comparison of the curves obtained from vitrain, spores, clarain, resin and fusain is also shown.

STATUS OF SUMMARY COAL RESOURCE SURVEYS, NOVEMBER 1, 1951.[1]

PAUL AVERITT.

Summary coal resource studies completed or in progress during 1951 show a continuation of the trend toward a moderate reduction of the older coal reserve estimates. More significantly, however, the newer estimates provide for the first time a breakdown of the coal reserve figures into categories according to the thickness of the beds, thickness of the overburden, and the relative abundance and reliability of the information available for making the estimates. Extrapolating from the small amount of classified summary reserve data now available it appears that roughly 15 percent of the total estimated reserves in the United States can

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be regarded as measured reserves in beds 28 inches or more thick under less than 2,000 feet of overburden; that an additional 15 percent can be regarded as indicated reserves within the same limits of thickness and depth below the surface; and that the remaining 70 percent includes inferred reserves, reserves in thin beds, or reserves 2,000 to 3,000 feet below the surface.

A consideration of this latter category, representing 70 percent of the total reserves, suggests that it includes as inferred a fairly large percentage of coal in the thicker beds, which for lack of detailed information cannot be appraised quantitatively. The percentage of measured and indicated reserves in the thicker beds under less than 2,000 feet of overburden will therefore increase an additional geologic and exploratory work on coal is completed.

REPORT ON THE THIRD CONFERENCE ON CARBONIFEROUS STRATIGRAPHY AND GEOLOGY AT HEERLEN, NETHERLANDS, JUNE 25–30.[2]

JACK A. SIMON.

The program of the 3rd International Conference on Carboniferous Stratigraphy and Geology held at Heerlen, Netherlands, June 25 to 30 inclusive is reviewed.

High points of the conference are pointed out with special emphasis on new data presented at the conference as well as a brief mention of observations on some of the key discussions.

SEDIMENTARY FACIES CHANGES IN COAL STRATA.

E. C. DAPPLES.

Association of certain strata with beds of coal, and the occurrence of such beds in repetitive vertical order, has resulted in the establishment of "typical" cyclothems, based primarily upon the fundamental units recognized in Illinois. Both to the east and west of this medial area components of an individual cycle are recognized with great difficulty. These departures from the ideal cyclothem are responses to primary differences in environmental conditions in part established by the tectonic behavior of the depositional site.

General aspects of variability of depositional conditions in scattered geographic localities are more clearly defined by the bulk lithology of a unit of rocks including several coal cycles, than in lithologic units within an individual cyclothem. The overall sedimentary facies of the large unit can be observed to change laterally as it is traced over an area including several states.

For purposes of illustration the lithologic variation within an interval of strata between two widespread coal horizons has been selected as an example of observed facies change. In some localities gradation between facies is rapid; whereas, in others there is little change between widely separate localities. Individual beds within the large unit often show great variability but they reflect the deviation from the average facies at a selected geographic point. The sedimentary facies of the large unit represents the "normal" condition and, therefore, indicates the nature of the "typical" cyclothem at that locality.

Tracing a finite unit over a wide area demonstrates the variety of conditions under which coal has accumulated. The mapped patterns which emerge lead to an understanding of the environmental-tectonic complex of which coal deposits are a part.

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INTERRELATION OF STRUCTURE AND PENNSYLVANIAN SEDIMENTATION IN CENTRAL ILLINOIS.[2]

E. P. DU BOIS.

Structural studies in Ts. 6 to 9 N., Rs. 4 E. to 4 W. show the fundamental pattern of late Paleozoic structure to consist of three north trending belts: an eastern St. James-Louden anticlinal axis, a central trough, and the western Illinois shelf area.

Stratigraphic variation in these belts includes pinching out of a thick sequence of lower Pennsylvanian sandstones against the eastern flank of the anticlinal zone, thickening of middle Pennsylvanian sediments in the trough, and thinning or overlap of beds in the shelf area. Coal is of normal thickness in the trough and shelf provinces but is thin over the anticline. Coal "cut-outs" may be erosional or may represent areas in which conditions of accumulation were unfavorable. In either situation, the underlying cause may be structural. An unconformity below the West Franklin limestone is noted and may be of widespread significance. The western limit of West Franklin limestone appears to be controlled by the presence of the St. James-Louden axis, whereas to the west, only massive sandstone is present at this approximate position.

The integration of structural and stratigraphic studies should be of aid in evaluation of coal reserves, interpretation of pre-Pennsylvania structure, location of stratigraphic traps, and other obvious applications. A program based on such studies, applied to larger regions and using appropriate sedimentological methods, will obviate the necessity for speculation and over-generalized theory.

SOME RECENT CORRELATIONS OF INDIANA COALS.

CHARLES E. WIER.

Various local names have been applied to the Indiana coals since 1850. As early as 1898 G. H. Ashley attempted to correlate these coals from one mining district to another, but due to lack of information many errors were made. Later Ashley and other workers made tentative correlations, still without sufficient evidence, and in many cases with conflicting conclusions.

Recent stripping has exposed excellent stratigraphic sections which, coupled with recent drilling information, have made exact correlations possible. This paper deals with correlations of Coals V, Va, Vb, VI and VII across Indiana. Coal V, with the overlying black fissile shale and Alum Cave limestone, is an excellent and continuous key horizon, but the younger coals vary considerably from one mining district to another.

SPORE ANALYSES APPLIED TO A COAL CORRELATION PROBLEM IN SOUTHERN INDIANA.

G. K. GUENNEL.

The age of the Millersburg coal of Warrick County has been debated since Fuller and Ashley named it in 1902 and correlated it with Coal VII. Logan, in 1922, inferred that the Millersburg is a combination of Coals VI and VII. The late Dr. Malott thought that Coal VI might be absent south of Monroe City in Knox County. In mining circles, however, the Millersburg coal is thought to be identical with Coal VI. The coal mined south of Elberfeld, by the Ingle Coal Company, and that stripped by the Sunlight Coal Company in the vicinity of Lynville, can be traced to Millersburg, Indiana, the type locality of the Millersburg coal. Spore

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analyses of the coal mine in these Warrick County localities show similar generic abundance patterns, substantiating this evidence. Thus the coal mined at Elberfeld and Lynville is the same bed, the Millersburg coal.

Samples of coal mined northeast of Winslow, Pike County, and southwest of Oakland City, Gibson County, which were thought to be Coal VI, were also examined. The resultant generic distribution patterns were compared to graphs derived for Coals VI and VII. A striking similarity is apparent between the graphs representative of the coals from Gibson and Pike Counties and the patterns representative of Coal VII. The distribution and abundance figures derived for the Millersburg coal, on the other hand, are dissimilar to the patterns representative of either Coal VI or Coal VII. The spore patterns for Coals VI and VII are quite diverse, so that any fused seam comprising both beds should show the same diversity. The upper part of the Millersburg, then, should resemble Coal VII in spore content, while the lower portion should be similar to Coal VI. However, this is not the case. The Millersburg coal revealed a uniform spore pattern, distinct from those representative of Coals VI and VII, leading to the conclusion that the Millersburg is not correlative with either Coal VI or Coal VII.

UNDERCLAY LIMESTONES.[2]

GEORGE M. WILSON.

Within the past eight years, more than 300 diamond drill holes, coring Pennsylvanian strata, have been studied by members of the Coal Division of the Illinois Geological Survey. One of the interesting features observed has been the marine limestones that sometimes occur beneath the underclay at the position of the underclay limestone. Often the lower part of the underclay contains small limestone nodules which increase in number and size until a solid limestone bench is developed.

These limestones have been examined megascopically and microscopically to determine the variation in the lithologic and faunal content. Several of these limestones contain well developed marine faunas, including fusulinids and croinoids. A study of the depositional and ecological environment of underclay limestones is necessitated as a result of the occurrence of the marine faunas.

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SCIENTIFIC NOTES AND NEWS

STUART ST. CLAIR, consulting geologist and engineer of New York, left some time ago for Europe and Asia on a professional trip of three to four months. His work will cover mining examination, petroleum investigation, and mineral economics. Prior to this trip he had been acting as consulting mining engineer to Defense Minerals Administration in Washington since early summer.

The Institution of Mining and Metallurgy, London, announces the election of VERNON HARBORD as President for the Session 1952–53. He will take office at the Annual General Meeting to be held on May 15th next.

At the request of the U. S. State Department, DR. WILLIAM B. MATHER, Southwest Research Institute's chairman of mineral technology, has been granted leave of absence by the Institute to participate in an economic mission to Brazil. This mission, called the United States-Brazil Joint Commission for Economic Development, is undertaken as part of Point Four program, and will be in the fields of industrial technology, mineral resources, and research.

HUGH E. MCKINSTRY was in Central Peru during July and August.

The 118th Meeting of the American Association for the Advancement of Science, the annual meeting for 1951, will include programs of all 18 of the Association's sections and about 45 participating societies. Focus of the approximately 225 sessions will be Convention Hall, adjacent to the University of Pennsylvania's School of Medicine and site of the 150-booth Annual Exposition of Science and Industry. A program of particular interest to geologists and conservationists will be a symposium on water entitled *The Nation's Water: Want, Waste, and Why?*, a part of the program of Section E, Geology and Geography, and presented in Room B, Municipal Auditorium (Convention Hall), Thursday, December 27, at 2:00 P.M. Those participating in the symposium will be: Chairman: Dr. A. N. Sayre, U. S. Geological Survey, Washington, D. C.; (1) "Water Supply in the United States," by Dr. J. R. Mahoney, Senior Analyst for Natural Resources, Legislative Reference Service, Library of Congress, Washington, D. C.; Discussors: Mr. Harry E. Jordan, Secretary, American Water Works Association, New York City, and Dr. Gilbert F. White, President, Haverford College, Haverford, Penna.; (2) "Some Implications of Multiple Purpose River Planning," by Mr. Morris L. Cooke, Consulting Engineer in Management, Philadelphia, Penna.; Discussors: Dr. Harold E. Thomas, U. S. Geological Survey, Salt Lake City, Utah, and Mr. R. M. Leggette, Consulting Ground-Water Geologist, New York City; (3) "Industry and Water Conservation," by Dr. Abel Wolman, Professor of Sanitary Engineering, The Johns Hopkins University, Baltimore, Md.; Discussors: Admiral Milo F. Draemel, Secretary, Department of Forests and Waters, Commonwealth of Pennsylvania, Harrisburg, Penna., and Mr. C. V. Youngquist, Chief, Division of Water, Department of Natural Resources, State of Ohio, Columbus, Ohio.

GEORGE W. TOWER, General Manager of Mines for M. Hochschild in Bolivia, spent a "long vacation" in New England in August and September.